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THE ROLE OF THE DEPARTMENT
DEVELOPMENT OF INTEGRA

Norman J. Asher
Leland D. Strom

May 1977

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The Department of Defense (DoD) was influential in the introduction of integrated circuits. This paper reviews the role played by DoD in their development and early use, and traces the resulting markets for integrated circuits and for products using integrated circuits. DoD provided R&D support during the early development of integrated circuits. Perhaps even more important was the creation of a market for integrated circuits through their incorporation into military systems. The early →

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20. military market provided the "learning curve" effect whereby unit prices decline as production proceeds. Within a few years, the integrated circuit unit price was low enough to penetrate the industrial market, and eventually the consumer market. In 1977, the value of integrated circuits being sold by U.S. firms is about $2.5 billion. However, integrated circuits are not an end product--they are only used in making other equipment. Hence, the value of equipment incorporating integrated circuits is considerably greater.

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FOREWORD

This paper has been prepared at the request of the Deputy Director (Research and Advanced Technology), Office of the Director of Defense Research and Engineering. In the past, DoD's RDT&E program has resulted in beneficial by-products in other government agencies and in the private sector of the economy. Prior studies of the civil product contribution from DoD funding of aircraft and engine development have shown there are private sector benefits from such programs. The objective of this paper is to investigate the DoD RDT&E and procurement programs in the field of integrated circuits and then to trace the impact of these programs on the resulting military, industrial, and consumer markets for integrated circuits.

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CONTENTS

SUMMARY

A comprehensive survey has been made of the various factors contributing to the early development and exploitation of integrated circuits in both military and commercial applications. Although the key initial inventions were provided by semiconductor industry funding, the Department of Defense (DoD) nurtured the semiconductor industry by providing both substantial R&D support and a large market for its products.

In 1958, DoD provided as much as 23 percent of the R&D funds to the semiconductor industry, not including the DoD Independent Research and Development reimbursement to industry. These funds were directed mostly towards electronic miniaturization and increased reliability. The Air Force program on molecular electronics was credited for stimulating thinking that led to integrated circuits. Following development of the first working integrated circuit at Texas Instruments in 1958, the Air Force awarded two contracts in 1959 and 1960 to Texas Instruments totalling $3.2 million for their development, including development of production processes. The DoD R&D support of integrated circuits continued in the range of $4-6 million over the period 1960 to 1964.

Of even greater importance than R&D support was the early creation of a military market for integrated circuits. In 1962 the Air Force contracted to use them throughout the Minuteman II guidance and control systems. This was the first large scale use of integrated circuits. In 1962 the DoD market for monolithic integrated circuits was virtually 100 percent of the

total dollar production, and was still as high as 53 percent in 1966 and 38 percent in 1968.

Other Government agencies, mainly NASA, also contributed to their development. In 1963, NASA R&D funding for integrated circuits was still only 5 percent of that of DoD, but this increased to 33 percent in 1964. During 1960-1970, total NASA funds for integrated circuits including procurement ranged between 10 percent and 40 percent of those of DoD.

The value of integrated circuits to DoD is measured not only by direct purchases, but also by the indirect effect on weapon systems with respect to their feasibility, cost-effectiveness, and reliability. DoD expenditures on integrated circuits rose rapidly from $4 million in 1962 to $126 million in 1967. It has since stabilized at about $140 million annually. Concerning indirect effects, their use in Minuteman II resulted in a 50 percent reduction in weight of the guidance package, an associated increase in range, twice the functional capability of the previous discrete model, increased reliability, and reduced logistics costs.

Another important factor was the DoD influence on the commercial market for integrated circuits, in particular providing the "learning curve" effect leading to reduced prices. The average unit price dropped from $50 in 1962 to $2 in 1968, during which period the military market predominated. The military insistence on high reliability also provided the impetus for quality improvement. Thus, the time span to commercial exploitation was considerably diminished.

In 1977, the value of integrated circuits being sold by U.S. firms is about $2.5 billion. Recent commercial applications include the initiation of new products such as handheld calculators, TV games, and electronic watches and clocks, and significantly improved performance/price ratios for data processing systems, automotive electronics, data communications (including satellites), industrial machine controls, consumer electronics (TV, Radio, HiFi, CB radios), and medical electronics (hearing aids, pacemakers, analytical equipment). In several of these areas, and in many others, we are seeing the application of integrated circuits as *microprocessors*, which are physically large-scale integrated circuits embodying generalized computer logic. From $300 million this year (1977), microprocessor sales are expected to grow to $1 billion by 1980.

THE ROLE OF THE DEPARTMENT OF DEFENSE
IN THE DEVELOPMENT OF INTEGRATED CIRCUITS

A. INTRODUCTION

Integrated circuits are an outgrowth of the semiconductor industry. They use basically the same materials and processes as are used in the production of discrete semiconductor components, such as transistors. As the name indicates, their novel feature is that many components can be imbedded in a single semiconductor "chip." The resulting integrated circuit has the following principal advantages over circuits composed of discrete electronic components: (1) lighter weight and smaller size; (2) increased reliability; and (3) reduced cost. These desirable features have permitted many previously existing products to become more cost-effective, and in addition have spawned new products such as digital watches and handheld calculators that would not have been developed if integrated circuits had not been available. These new and improved products have greatly increased the cost-effectiveness of many activities--initially in the military field and subsequently in the industrial and consumer fields.

The Department of Defense (DoD) was influential in the introduction of integrated circuits. This paper reviews the role played by DoD in their development and early use, and traces the resulting markets for integrated circuits and for products using integrated circuits.

B. THE ROLE OF DoD IN THE INVENTION AND DEVELOPMENT OF INTEGRATED CIRCUITS

A great deal of literature exists on the development of the integrated circuit. There is a remarkable consistency in the conclusions reached by writers representing many points of view: principal players, the public press, government agencies, industry, university students, research organizations, and foreign as well as U.S. publications. Pertinent material from many of these publications is presented at the end of this Section.

The first working integrated circuits were invented in late 1958 by Jack Kilby at Texas Instruments. Soon afterwards, a major advance in its practicality was made through the development of planar technology under the leadership of Robert Noyce at Fairchild Semiconductor Division. In both cases the work was carried out under company funding; DoD can claim no direct credit for the invention of the integrated circuit. However, the integrated circuit was dependent upon the technology of the semiconductor industry, and DoD had nurtured the semiconductor industry by both heavy R&D support and by providing a large market for high quality semiconductor products. Furthermore, following the invention of the integrated circuit, DoD again provided R&D support to its development and, probably more importantly, accelerated the use of integrated circuits by providing the early market which supported the development of production capability.

There are strong incentives for industry to selectively fund with its "own money" techniques, processes, or products (such as integrated circuits) that have large potential payoffs, either military or civilian. In this way, a given company can establish "background" patent rights and also can claim proprietary rights (even if not patentable) for certain techniques, processes, and products. Thus, industry may be motivated to fund the early conceptual phases and small-scale laboratory development of new devices. For follow-on phases, including initial development of manufacturing methods, it may use Independent Research and Development funding provided by government reimbursement of overhead. Then, for those devices for which there is a market, it will seek government funding of pilot or initial production run manufacturing, including, in some cases, the funding of facilities. This general pattern was followed by industry in the development of integrated circuits.

Acknowledging that DoD was not directly involved in the invention of the integrated circuit, let us first examine DoD's role in the semiconductor industry before the invention of the integrated circuit and then its support of integrated circuits following their invention.

1. The Role of DoD before the Invention of the Integrated Circuit

The great influence of DoD on the semiconductor industry can be seen from the R&D figures of Table B1. These figures, published by the National Science Foundation (NSF), are for "electronic components and communication equipment." Semiconductor components are included in these figures but are not broken out separately by the NSF. As can be seen, the government (mainly DoD) was providing most of the R&D funding for equipment falling in these Standard Industrial Classification (SIC) codes in the 1957-1958 period. A special survey indicated that DoD was providing relatively less but still a significant portion (approximately 23 percent) of R&D funds to the semiconductor industry in 1958 [4].

In addition to its funding of R&D in the semiconductor industry, DoD was also a major buyer of semiconductor products. Reference [4] reported that DoD purchased about 40 percent (in dollar terms) of the semiconductor shipments in the late 1950's.

In addition to DoD funding support of both R&D and production, the services created a market environment that encouraged the development of the integrated circuit. All of the services had various programs aimed at electronic miniaturization and increased reliability. The one that proved to be most similar to the integrated circuit was the Air Force molecular electronics concept. Although the practical integrated circuit was not a

Table B1. GOVERNMENT AND INDUSTRY R&D FUNDS FOR ELECTRONIC COMPONENTS AND COMMUNICATION EQUIPMENT (SIC CODES 366, 367, 48), 1957-1968

(Millions of Dollars)

Year	Government	Industry	Total
1957	518	230	748
1958	615	253	868
1959	855	308	1,163
1960	944	380	1,324
1961	934	470	1,404
1962	1,074	517	1,591
1963	1,209	564	1,773
1964	1,259	613	1,872
1965	1,292	697	1,989
1966	1,428	821	2,249
1967	1,495	930	2,425
1968	1,538	1,000	2,538

Source: *Research and Development in Industry*, 1969 and 1973 issues, National Science Foundation, NSF 71-18 and 75-315, respectively.

direct result of the Air Force program, the concepts were quite similar, and the Air Force program stimulated thinking that led to the integrated circuit.

2. The Role of DoD after the Invention of the Integrated Circuit

Following the development of the first working integrated circuit by Jack Kilby of Texas Instruments (TI), the Air Force quickly realized its importance and in June 1959 awarded a $1,150,000 contract to TI for its further development. Another $2,100,000 contract was awarded TI in December 1960 for the development of production processes and special equipment needed for the fabrication of integrated circuits in bulk quantities [14]. The Air Force and the other services supported integrated circuit R&D with other companies as well in the first few years of integrated circuit development.

The continued heavy involvement of the government (mainly DoD) in that segment of the electronics industry including integrated circuits, for the few years following their invention, also can be seen in Table B1.

Perhaps even more important than R&D support was the creation of a market for integrated circuits through their incorporation into military systems. In 1962 the Air Force contracted with the Autonetics Division of North American Aviation to use integrated circuits throughout the Minuteman II guidance and control systems. This was the first large scale use of integrated circuits. The use of integrated circuits in many other systems of all the services, as well as by NASA in the space program, quickly followed. Defense production of monolithic integrated circuits as a percentage of total production (in dollar terms) was estimated by Tilton [2] as follows:

Year	Percent of Total Production
1962	100%
1963	94
1964	85
1965	72
1966	53
1967	43
1968	37

Note that the above figures are for monolithic integrated circuits only; the DoD percentage of all integrated circuits was considerably lower. However, monolithic integrated circuits offered the greatest potential for improvement over the previous generation of discrete semiconductor components.

The early military market provided the learning curve effect whereby unit prices decline as production proceeds.

Within a few years, the integrated circuit unit price was low enough to penetrate the industrial market, and eventually the consumer market. As can be seen in Table B2, in 1962, the year after they were introduced, their average price was about $50. By 1968, the price had fallen to about $2 and by 1972 it was about $1. Unfortunately, the reporting series of Table B2 was discontinued after 1972. In addition to the price reduction, the military insisted on high reliability, so that the quality of integrated circuits improved over this period of time. It is widely agreed that this early military market advanced the time when integrated circuits would economically penetrate the nonmilitary market sectors.

Table B2. AVERAGE VALUE OF MONOLITHIC AND MULTIPLE CHIP INTEGRATED CIRCUITS

Year	Unit Value (Dollars)
1962	$50.00
1963	31.60
1964	18.50
1965	8.33
1966	5.05
1967	3.32
1968	2.33
1969	1.67
1970	1.49
1971	1.27
1972	1.03

Sources: 1962 and 1963: [2, Table 4-8]; 1964-1972: [20, Table 78].

3. Key Evidence from the Literature on DoD's Role in the Development of Integrated Circuits

The following excerpts from the literature summarize key evidence on the role of DoD in the development of integrated circuits. These excerpts are grouped according to the various types of sources.

3.1. Principal Players

Jack Kilby acknowledged Air Force support following his development of the first working integrated circuit [10]:

> Albert's group [at WADC] then provided the first of a series of contracts which proved invaluable in sustaining the project during the critical years. These included both research and development efforts to broaden the concept, and manufacturing methods funds which helped support the first manufacturing line. Demonstration vehicles which clearly showed the advantages of these new techniques were also included.

In an article on "The Genesis of the Integrated Circuit" [21], the author reported that:

> Although the work at TI and Fairchild was not the molecular electronics the Air Force was advocating, and although Fairchild intentionally avoided Government funding for its efforts, Kilby and Noyce agree on the importance of the military in establishing the motivation to miniaturize as well as in ultimately becoming the first customer for the new circuits.

Drs. Linvill and Hogan reported [5]:

> As early as 1959, the services supplied another $10 million to American industry to buy or build the equipment necessary to build a production capability for integrated circuits.

3.2. Ph.D. Dissertations

Dr. Kleiman stated in his dissertation submitted in 1966 [15]:

> The technology, more so than any other innovation in the electronics industry, represents a new

> approach nurtured and supported by Government funds. It has since been utilized not only in military and space programs, but has "spun off" to many non-Government applications.

Dr. Golding, a Britisher, noted in his 1971 dissertation [3]:

> The primary impetus for microelectronics has been provided by the three military services in the U.S.A.

3.3. Research Organizations

Arthur D. Little, Inc., noted the role of DoD in the development and early production of integrated circuits [16]:

> By 1958, Texas Instruments had perfected the first integrated circuit, a single-phase shift oscillator circuit made of germanium.... The subsequent development pace accelerated rapidly, aided particularly by substantial Government contracts, mostly from the Air Force.

Tilton, in a 1971 Brookings Institution book [2], noted the primacy of the military market in the early days of integrated circuits:

> When this new device was first introduced into the market, it was expensive compared to the discrete semiconductors it could replace and so was used almost exclusively in government equipment, particularly in missiles where performance, not cost, had top priority.

A 1973 report prepared by Pacific Projects, Ltd., stated [12]:

> In the United States, a substantial amount of R & D is sponsored by the Federal government and stimulated by U.S. space and military procurement, especially in the field of IC development.

3.4. Industry

The Autonetics Division of North American Aviation described its early applications of integrated circuits in a 1966 publication [7]:

"Birth" is usually described as the occasion upon which an entity makes its first appearance in the big, outside world, and actually begins to live. Microelectronics first saw the light of day in many areas of application. For all practical purposes, however, the birth of microelectronics took place with its use throughout Minuteman II in 1962--for this was the first time microelectronics began to "live"--in its overall mechanization of an entire defense weapon system.

3.5. U.S. Government

In 1965 the Air Force published a history of its involvement in the development of integrated circuits [14]. In the Foreword, Gen. B. A. Schreiver stated:

> The birth and explosive growth of integrated circuits can be directly attributed to a combination of wise policy direction by the Department of Defense; initiative, stimulation and dynamic management by the Air Force Systems Command; and spirited response by industry.

3.6. International Organization

A 1968 study by the OECD [1] noted the importance of the early U.S. military market:

> As for integrated circuits, the present [1968] very rapid growth rate can to a large extent be explained by the tremendous expansion of the computer industry; in 1963-1964, the impetus was coming from another market, namely that for missiles.

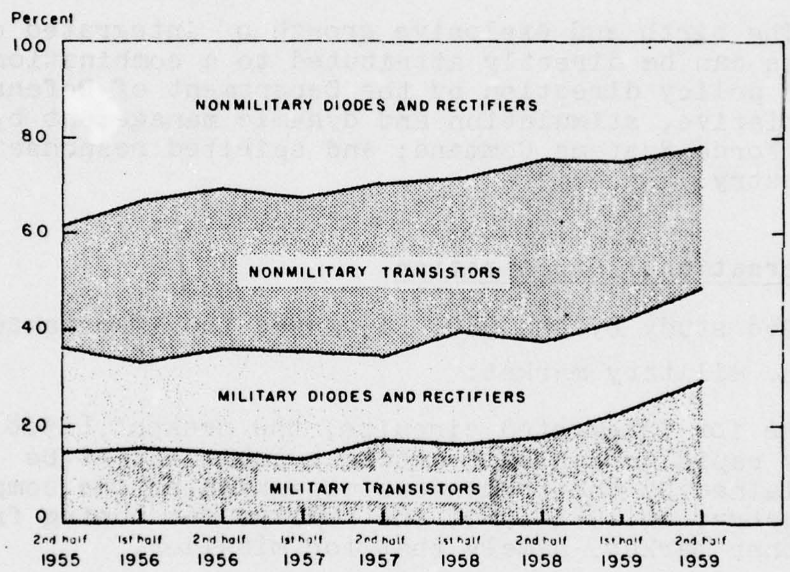
4. Excerpts from the Literature

More complete excerpts dealing with the role of DoD in the development of integrated circuits are presented below in the approximate chronological order of their publication. Table and figure numbers are retained as they appeared in their original source.

1961 Department of Commerce Survey

In 1961, the Department of Commerce (DoC) published a survey of the semiconductor industry [4]. At that time integrated circuits were in the early stage of development and were not dealt with explicitly in the DoC study. However, the study did discuss the importance of the military market to the semiconductor industry, which at that time was developing integrated circuits. The following graph shows relative shipments (in dollar terms) to the military and nonmilitary markets:

Relative Distribution of Semiconductor Shipments
Military and Nonmilitary, 1955-59



Source: Joint EPRA/BDSA Survey

The DoC publication also included data on government R&D support to the semiconductor industry:

> A part of the research is being financed by the Government through R & D projects and production-refinement projects, or Industrial Preparedness Studies (IPS) (Table 8).

Table 8.--Estimated Funding of Programs in the Semiconductor Area, 1955-61
[In thousands of dollars]

	1955	1956	1957	1958	1959	1960	1961
Research and development..	3,169	4,052	3,798	4,010	6,300	6,800	11,000
Industrial preparedness studies: transistors...	2,710	14,000	0	1,900	1,015	0	1,650
Industrial preparedness studies: diodes and rectifiers............	2,240	850	500	200	0	1,110	800
Total...............	8,119	18,902	4,298	5,910	7,315	7,900	13,450

Source: Department of Defense Advisory Group on Electron Tubes.

In addition, some of the funds spent by the Department of Defense for work on the development of weapons systems are passed on by prime contractors to components manufacturers. In order to obtain information on the size and source of R & D funds, the Department of Defense made a special survey in mid-1960 (Table 9).

Table 9.--Research and Development Expenditures
[Millions of dollars]

	1958	1959	January-April 1960
Government funds, total..........	13.9	16.2	6.8
Department of Defense..........	12.6	14.4	6.3
Other..........................	1.3	1.8	0.5
Company funds......................	41.8	54.6	25.4
Total funds.................	55.7	70.8	32.2

Source: Department of Defense Survey, May 1960.

The DoD figures in Table 9 are greater than those of Table 8 because they include semiconductor R&D funds imbedded in prime weapon system contracts, whereas the figures of Table 8 cover R & D projects only. The DoC Table 9 above indicates that DoD provided 23% of total semiconductor R & D funds in 1958 and 20% in 1959 and early 1960.

1962 Article in *Aviation Week and Space Technology*

A 1962 article in *Aviation Week and Space Technology* discussed the impact of microelectronics (integrated circuits) on the avionics industry [8]. This article is particularly interesting in that it was written before the first large scale production application of integrated circuits in Minuteman II and yet it predicted accurately the coming widespread impact of integrated circuits in avionics. The article clearly shows the dominance of the military market in the early applications of integrated circuits (italics added):

> A few systems outfits are going into semiconductors in the belief, properly founded or not, that *the military, principal end users of microelectronics*, may want it that way. *A small but increasing number of proposal requests for studies, and in certain cases hardware, specify microelectronics*--at times where the value of its use is dubious. *Many military agenices view microelectronics very favorably*, not exclusively for valid reasons, in the opinion of these equipment suppliers. *Spokesmen of one agency in particular have been among the most ardent advocates of microelectronics* and to ignore this, these people believe, and not to have a microelectronics capability about which to boast in equipment proposals, is to risk one's chances of winning contracts.

The article discussed the possible use of integrated circuits in a growth version of Minuteman, which later was realized in Minuteman II:

> Autonetics and the Air Force may go microelectronic in the longer-range, growth version of Minuteman, perhaps employing integrated circuits in highly repetitive logic sections of the guidance computer, discrete micro components in platform electronics. If this happens, the the pace and direction of microelectronics could change overnight.

The article went on to discuss other possible applications of integrated circuits and related research, mostly for the military market (italics added):

Meanwhile dozens of demonstration and feasibility equipments which use integrated circuits, micro components, thin films or combinations of these are being built throughout the country, *a number under government contract*. Typical, perhaps, is a unit designed for *the Samos photo reconnaissance satellite system* which will employ thin film circuits with discrete uncased semiconductor components in one section, integrated circuits in another section and welded modules in another. An integrated circuit digital guidance computer is being fabricated to meet anticipated specifications for the stellar inertial guidance system of *mobile medium range ballistic missile (MMRBM)*. At Navy request, the possible use of integrated circuits in *a navigational computer for two types of naval aircraft* is under evaluation. International Business Machines, one of the largest potential users of microelectronics in its commercial as well as *military navigational computers*, and *a systems organization with a large internal non-commercial component department*, is building a full-sized computer with micro components mounted on circuit cards for evaluation.

...Of many companies initially attracted into integrated circuits for the financially rewarding digital market, a growing number are now investigating the linear area and seeking flexible production techniques which would enable them to make small quantities economically. *Motorola's broad program, heavily supported by the Air Force, is probing this area (AW Jan.8, p.85), Texas Instruments is developing a PCM telemetry encoder for USAF (AW Nov.6, p.83)* and *the Army Signal Corps is conducting an industry competition for a continuous wave linear amplifier.*

...Single crystal semiconductor films on foreign substrates are the subject of a sudden burst of *military research interest* with a series of programs being launched by *USAF's Aeronautical Systems Division and the Army Signal Corps.*

1965 Air Force History of Integrated Circuits

In 1965 the Air Force--the leading service in the development of integrated circuits--published a history of its involvement in that area [14]. In the Foreword, Gen. B. A. Schreiver stated:

The birth and explosive growth of integrated circuits can be directly attributed to a combination of wise policy direction by the Department of Defense; initiative, stimulation and dynamic management by the Air Force Systems Command; and spirited response by industry. The story is dramatic proof that the frontiers of our technology can continue to be rolled back by intelligent and imaginative assumption of risk, proper allocation of resources, and reliance on scientific ingenuity.

It is important to understand that this technology was based on a growing operational problem rather than the normal evolution of a new technical phenomenon. The problem demanded a major scientific advance involving considerable financial and technical risk. The solution proposed by the Air Force was criticized by some and questioned by others. The fact that the technology was successfully developed makes it important to review and comprehend the degree of participation of our government laboratories, so that existing and future programs may profit by the lessons learned.

The report discussed the early molecular electronics approach of the Air Force:

Air Force management, working together with such organizations as Westinghouse, evolved the concept of *molecular electronics*: a single piece of solid material synthesized to achieve a complete circuit function. Dr. H. V. Noble and other research directors at the Wright Air Development Center (WADC) were the first to propose, in 1953, development of these functional electronic blocks for the Air Force. Nothing concrete resulted at this early date. But the direction in which the Air Force ultimately would move had been set. During the period 1956 to 1958, Air Force study groups established specifications for improved reliability in electronic equipment. Their studies confirmed that a drastic improvement was needed. Col. C. H. Lewis and Mr. F. E. Wenger of the Headquarters Air Research and Development Command (ARDC) supported by the group under Dr. J. E. Keto at WADC, documented in 1958 the need for solid blocks of material capable of performing a complete circuit function.

The report then went on to discuss the integrated circuit approach to molecular electronics:

Another approach to molecular electronics, called integrated circuits, was emerging. The integrated circuit concept involves a block of transistor-type solid material in which individual areas are also synthesized to obtain certain electrical properties such as resistance. These areas are interconnected within the block to perform for the first time in a solid block a complete circuit function, similar to the way in which individual parts are used to make up a conventional circuit.

The origin of the integrated circuit concept is traced to G. W. A. Dummer of the British Royal Radar Establishment who, at the May 1952 Electronic Components Conference in Washington, D.C., stated:

> "With the advent of the transistor and the work in semiconductors generally, it seems now possible to envisage electronics equipment in a solid block with no connecting wires. The block may consist of layers of insulating, conducting, rectifying and amplifying materials, the electrical functions being connected directly by cutting out areas of the various layers."

This idea, and the inventions of such early innovators as J. S. Kilby and Dr. H. W. Henkels, are the roots of the integrated circuit as we know it today.

In summary, there existed a defined need, proposed to be satisfied by a vague research concept known as molecular electronics. There also existed a specific development, with no defined goal, evolving from the advancing semiconductor technology. It will now be shown how these were merged into one vital effort.

The report described the early molecular electronics contract with Westinghouse:

In 1957, the over-all industry response to Air Force interest in molecular electronics was unenthusiastic. Nevertheless, the Air Force and, in particular, the Aero-Electronics Directorate of the Air Research and Development Command (ARDC) and the Electronic Technology Laboratory of Wright Air Development Center, actively supported immediate initiation of a research and development program in molecular electronics. Finally, in late 1957, Colonel Lewis and other ARDC staff members after surveying industry reaction struck a responsive chord at Westinghouse.

...At the time in 1958 when the molecular electronics program was proposed, the Air Force already had apportioned all its research and development funds for fiscal year 1959. But with the very active support of James M. Bridges of the Office of Defense Research and Engineering of the Department of Defense, $2,000,000 in emergency funds were provided to start the program. The proposed plan called for spending that money in only ten months at Westinghouse--an approach severely criticized by both the scientific community and AGET, because it was based on "abstract" requirements and not scientific fact. Fortunately, however, this conservative attitude was overruled and the contract begun in April 1959.

Westinghouse and the Air Force spent a difficult year attempting to deliver solid evidence of accomplishment: namely, working circuit blocks. Also undertaken were system studies exploring the possibility of utilizing molecular electronics in specific pieces of electronic equipment then in use. The success of this initial contract led to a $2,600,000 extension in early 1960.

The report described the early work at Texas Instruments, conducted with company funds, and the quick Air Force supportive response to this work:

As a logical outgrowth of the rapidly expanding transistor technology, the feasibility of building integrated circuits had been discussed as early as 1955 at Texas Instruments by P. J. Haggerty, President, and Dr. W. Adcock, Director of Research. In 1958, J. S. Kilby of Texas Instruments succeeded in fabricating the first complete circuit in a single piece of material. The single material block contained the equivalent elements for individual components, such as transistors, resistors, and capacitors, all interconnected in one circuit. Reliability was increased greatly since component interconnections were thereby eliminated.

By October 1958, working models of two types of circuits, oscillators and multivibrators, had been fabricated. These were shown to Captain E. B. Richter of the Air Force Electronic Technology Laboratory of WADC, who reported on their development. Demonstrations were arranged for Dr. H. V. Noble and Mr. R. Alberts of WADC. Based on these demonstrations the Air Force proposed a development program to be conducted at Texas Instruments to exploit this promising breakthrough in circuit fabrication. Again, by imaginative planning and concentrated funding, the Air Force proposed to bring a new development to practical fulfillment in a short time.

In June 1959, a $1,150,000 contract was awarded to Texas Instruments. The contract called for the development of integrated circuits capable of performing several specific circuit functions. Rapid progress using silicon as the basic material resulted in the development of practical models of various circuits.

In late 1960, research and development had progressed so rapidly that the integrated circuit was outgrowing its status as a laboratory curiosity. Air Force planners recognized that production facilities soon would be required if the laboratory advances being made daily were to be applied to new equipments then being designed. To keep pace with this growth, the Air Force awarded to Texas Instruments in December 1960 a $2,100,000 production refinement contract for the development of production processes and special equipment needed for the fabrication of integrated circuits in bulk quantities. The contract resulted in a pilot assembly line, capable of turning out 500 integrated circuits a day.

THE FIRST INTEGRATED CIRCUIT EQUIPMENT

As late as 1961, the industrial and scientific communities still voiced doubts as to the worth of integrated circuits from an equipment and systems viewpoint. To alleviate these doubts, and to further exploit the experience obtained under the earlier equipment-oriented Westinghouse program, the Air Force proposed the building of a representative piece of electronic equipment using integrated circuits.

Under Air Force sponsorship, the building of a digital computer was introduced into the Texas Instruments production program. Two identical computers were built: one with 9000 individual components, and one containing only 587 integrated circuits. Demonstrations of these two equipments in October 1961 were made to packed technical audiences in Dayton, Washington, and Los Angeles. The joint Texas Instruments-Air Force demonstrations were given by P. J. Haggerty of Texas Instruments, and Col. A. Wallace, Mr. R. Feik, and Capt. L. Roesler of the Air Force.

The success of the demonstrations in obtaining acceptance of integrated circuits was revealed by renewed industry interest. Companies that had been watching from the sidelines the progress of the Air Force-supported programs at Westinghouse and Texas Instruments began company-funded research and development programs. Fairchild, without government support and spurred by the increasing tempo of government and industry efforts, developed its first circuits in 1961.[1]

...The rapid development of the integrated circuit concept during these early years was due in large part to effective management and unequivocal support by the Air Force. The overall achievement was the merging, with spectacular results, of two separate programs--one to satisfy a critical military need for reliability; the other to advance the state of transistor technology. Out of this came the first significant molecular electronic device: the silicon integrated circuit.

Air Force involvement in the development of integrated circuits continued:

Momentous technological advances in the design and fabrication of integrated circuits were made between 1961 and 1964. The Air Force sponsored a program at Motorola to improve integrated circuits by combining the best characteristics of thin-film technology with the integrated circuit.

...Once the feasiblity of integrated circuits was established, the next step was their application to electronic equipments. To demonstrate the feasiblity of these applications, the Molecular Electronics Group at Wright-Patterson Air Force Base originated, and had included in the original Westinghouse contract, the *systems research vehicle concept*. This concept involves the building of demonstration equipments to prove the validity of utilizing integrated circuits where transistors previously had been used.

The group, under R. D. Alberts, sponsored the development of three pieces of electronic equipment utilizing integrated circuits: a communications receiver, a telemetry encoder, and an infrared tracker. The construction of these equipments contributed a significant amount of new knowledge to the design of integrated circuit equipment--and the successful accomplishment of these projects resulted in a new approach to equipment design.

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[1] Author's Note: More precisely, Fairchild marketed its first integrated circuits in 1961; they were developed during 1959 and 1960.

The report then described the first use of integrated circuits in a major system--Minuteman II:

> In 1962, the Autonetics Division of North American Aviation and the Air Force Ballistic Systems Division were in the midst of a design improvement program for one of the country's most important weapon systems: the Minuteman intercontinental ballistic missile. An improved Minuteman capable of longer range with no decrease in payload or reliability was needed. To design a new, higher performance propulsion system would involve a costly and lengthy program of propulsion system development and testing. The only other way to increase the missile's range was to reduce the size and weight of the existing electronic guidance package.
>
> At this time, three possibilities for electronic miniaturization existed: thin films, Micro-Modules, and the integrated circuit. After exhaustive research, Autonetics proposed to the Air Force the use of the then emerging integrated circuit technology. In 1962, Minuteman II became the first major weapon system in development using integrated circuits.
>
> Two years later, the first Minuteman II guidance computer using integrated circuits was successfully flight tested. A 50% reduction in weight with a resulting increase in range of many miles, and significant improvement in equipment reliability was achieved. Successful completion of this computer in such a short time served notice that integrated circuits must be accorded a competitive position in every future system design. The decision to use integrated circuits was of particular importance to the semiconductor industry. The prospect of large production orders justified capital expenditures by industry for integrated circuit research and development.

The report described other early programs and their stimulation of interest by the semiconductor industry in the field of integrated circuits:

> Success of the systems research vehicle concept, and of the Minuteman II guidance computer, made obvious the inherent benefits of integrated circuits. The quickest way to take advantage of these benefits was to completely redesign existing equipment, using available integrated circuits. Marine Corps Col. A. Lowell of the Navy Bureau of Weapons, an ardent exponent of exactly this approach, started a broad program to place integrated circuits in Navy equipment

in the shortest possible time. His first efforts involved direct replacement of printed circuit boards containing individual components by boards using integrated circuits. The production orders which resulted gave needed support to the emerging integrated circuit industry. Proposed integrated circuit development programs for a Loran C navigation receiver at Sperry, an integrated helicopter avionics system, and an integrated light attack avionics system also encouraged many companies to enter the field.

Colonel Lowell's continued advocacy of integrated circuits was an important factor increasing industry's production capability. Large orders for integrated circuits--200,000 units for the NASA Apollo guidance computer; the $9,000,000 Minuteman II contract--produced rapid expansion at Texas Instruments, Westinghouse, Motorola, and Fairchild. New companies, such as Signetics, Siliconix, General Micro-Electronics, and Molectro were founded primarily to manufacture integrated circuits. Interest was increased at RCA, Sylvania, Raytheon, and TRW. Equipment manufacturers, such as Radiation Incorporated, Melpar, Collins Radio, and Norden started their own research and development programs to keep up with the rapid advances in integrated circuit technology.

The report included a description of several major military applications of integrated circuits as of its issue date (1965):

Minuteman II

Phoenix air-to-air missile

Mark 48 torpedo

Cable sonar submarine-detection system

AN/UCC teletypewriter radio transmission system

Navy E-2A aircraft

USMC tactical data system

AN/GXC facsimile equipment

TF-600 secure communications system

Laser rangefinder

Lance missile telemetry equipment

PCM data buffer subscriber set.

This Air Force report presents persuasive evidence that DoD accelerated the development of integrated circuits to the point where they could be used commercially. Both direct support of R&D and the early military production program contributed to the subsequent commercial use of integrated circuits.

1966 North American Aviation Report

As previously noted, the first large scale production use of integrated circuits was in the Minuteman II missile. The Air Force contracted with the Autonetics Division of North American Aviation for this work. The Autonetics Division described its early applications of integrated circuits in a 1966 publication [7]:

> "Birth" is usually described as the occasion upon which an entity makes its first appearance in the big, outside world, and actually begins to live. Microelectronics first saw the light of day in many areas of application. For all practical purposes, however, the birth of microelectronics took place with its use throughout Minuteman II in 1962--for this was the first time microelectronics began to "live"--in its overall mechanization of an entire defense weapon system.
>
> ...First-generation microelectronics is in daily, world-wide use for *heightened* reliability, enhanced performance, lowered cost, smaller volume and weight, and increased range and payload...in the electronic guidance, control, communication, and data processing systems of industry, science, NASA, the Army, Navy, and Air Force...and will continue to be for quite some time.
>
> ...Minuteman II has become the largest consumer of semiconductor integrated circuits, as deliveries of this type of microelectronics in mid-1965 climbed past the half-million mark for the missile's guidance and control. Each missile uses about 2400 semiconductor microcircuits, plus another 600 for associated ground support equipment and test quantities. Dollar volume of Minuteman microcircuit purchases in 1965 accounted for about 20% of total industry sales.

The importance of the Minuteman II program in providing the first large scale production of integrated circuits was also reported in a July 1965 article in *Aviation Week* [11]:

> Minuteman ICBM program has become the largest single consumer of semiconductor microcircuits, as

unit deliveries for the missile's guidance and control systems climbed past the half-million mark last month.

North American Aviation's Autonetics Div., associate prime contractor for the Minuteman guidance and control systems, had requisitions for another 600,000 circuits outstanding at the same time. Delivery rate has reached 15,000 circuits per week.

Average microcircuit selling price is declining sharply, dipping to about $12 per circuit in July from $18 earlier this year. Total dollar volume of Minuteman microcircuit purchases is believed to account for about 20% of industry sales.

Texas Instruments and Westinghouse are the principal Minuteman microcircuit suppliers with the former accounting for more than 60% of unit deliveries, the latter about 35%.

Each Minuteman 2 missile uses about 2600 semiconductor microcircuits, plus another 200 for associated ground support equipment and test quantities. Systems for about 350 Minuteman 2 missiles are being built at the rate of 6-7 per week, with production scheduled to be complete by early fall of 1966. Production of an additional 165 missiles at a slightly slower pace is expected to begin in October, 1966.

The Autonetics publication [7] included material on the expanding use of integrated circuits growing out of the company's experience in their use in the Minuteman program:

Microelectronics' record-breaking report card on Minuteman has led to its use in all Autonetics' systems--computing, navigation, flight control, radar and ground support equipment. The Company approached as 1966 started, a requirement of 100,000 integrated circuits per month. Dollar-wise, Autonetics procured at that time approximately 25% of all the semiconductor integrated circuits procured in the entire U.S.A.

...As of late 1965, Autonetics had over 800,000 semiconductor IC's in use...approximately 850,000 additional IC's on order...over 177,000,000 IC/hours of operation.

...The team concept of Autonetics and its suppliers demonstrated so successfully on Minuteman I was adapted to procurement of microelectronic circuity and components for Minuteman II. In cooperation with suppliers,

> Autonetics designed solid-state microcircuits to give Minuteman II longer range, increased payload, higher reliability, reduced logistics costs--and then worked closely with suppliers to put microcircuits into production without degrading the design goals.
>
> ...Autonetics' systems talents and achievements cover a broad gamut--computers, autonavigators, radars, armament and flight controls, and ground support equipment. All of these systems use microelectronics to assure high-calibre performance and cost-effectiveness of the programs on which they serve.

The Autonetics publication went on to describe the use of integrated circuits in the R45 Multimode Airborne Radar System, the R47 System-Backup Radar, the Semiactive Guidance System (SAGS), the D26 computer family of microminiaturized, real-time data processors, the "Trisafe" triple redundant automatic stability augmentation system, and the N16 inertial navigation system. The importance of military applications in promoting the introduction of integrated circuits can be seen from the fact that nearly all of these early integrated circuit equipments were developed for the military.

1965 Arms Control and Disarmament Agency Report

An ACDA report noted the importance of defense needs in the development of integrated circuits [13]:

> The technology developed because of defense needs is of great importance in exploiting new developments or laying the groundwork for the developments. Examples are:

Development	Defense Need
⋮	⋮
Integrated Circuits	Need for low-power, lightweight computers for aircraft and missiles.
⋮	⋮

As part of the ACDA study, Battelle Memorial Institute conducted a survey of electronics companies. Figure 7 from the ACDA report shows the survey results for 150 companies on their views as to the importance of defense for nondefense products and technology. The report summarized these results as follows:

> There is a great divergence of opinion concerning the relative importance of defense support for diversification into new fields. The Battelle study has shown that this is also dependent upon the size of the company. The results from the survey are shown in Figure 7. The technology developed on defense contracts is considered to be more important than the direct fallout in products. The smaller companies capitalize more on products, possibly because they may have a much narrower product mix and are often component oriented (where defense and nondefense products are similar). Component companies in general may sell only two or three types of products and therefore see a much greater fallout than a company which sells a complete system tailored to a very specific application. However, all of the companies tend to emphasize the importance of technology for developing or for even looking at new areas for new products.

1965 and 1967 Arthur D. Little Reports

Arthur D. Little, Inc., issued a report on integrated circuits in 1965 [16]. The report included the following material on the role of DoD in the development and early production of integrated circuits:

> By 1958, Texas Instruments had perfected the first integrated circuit, a single-phase shift oscillator circuit made of germanium. Westinghouse Research Laboratory was engaged in similar work, and RCA was working on combinations of field effect transistors in a monolithic array. The subsequent development pace accelerated rapidly, aided particularly by substantial Government contracts, mostly from the Air Force,.... In 1964, the first large-scale application of integrated circuits was made jointly by Texas Instruments and the Autonetic Division (North American Aviation) to the guidance computer of the Minuteman II missile.

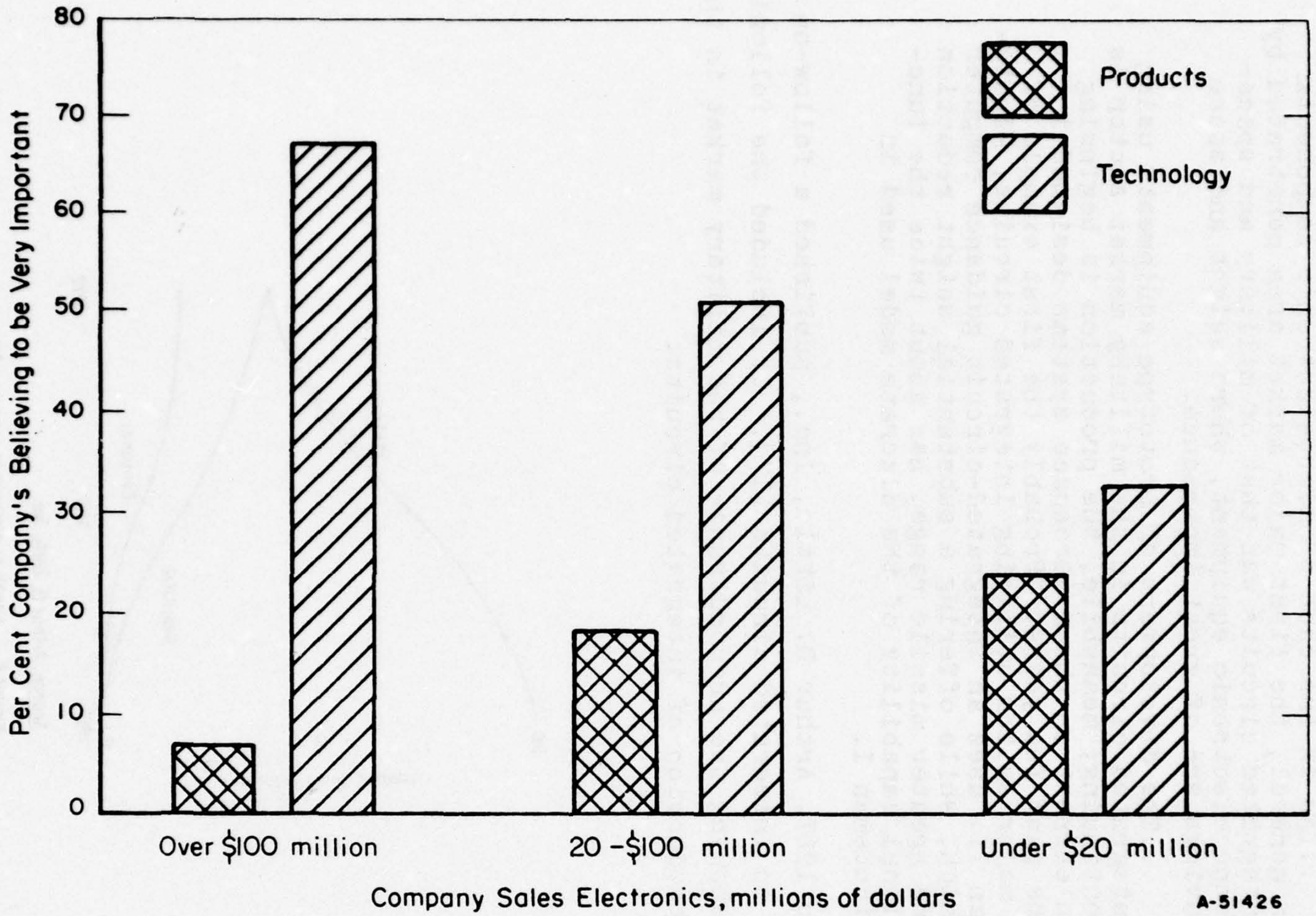


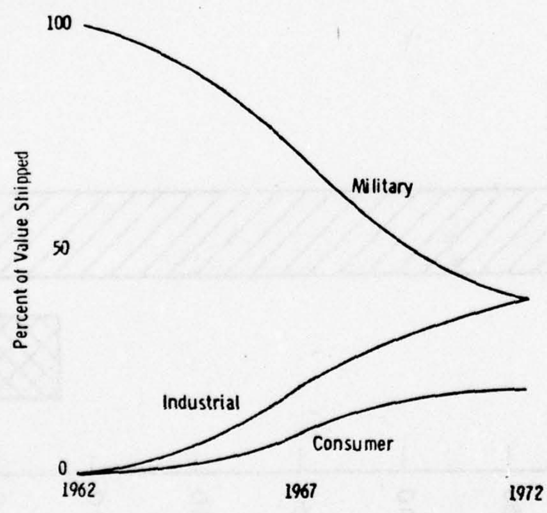
FIGURE 7. IMPORTANCE OF DEFENSE FOR NONDEFENSE PRODUCTS AND TECHNOLOGY

Source: Battelle Industry Survey

...As in the case of microelectronic components in general, the first major market area penetrated by integrated circuits was that of military and spaceborne electronic equipment, where weight and space savings are of great importance.

...The development of prototype equipments using integrated circuits in the military market sector is continuing; meanwhile, the production is beginning in earnest on those aerospace systems designed in the past few years. Probably the first example of a major system utilizing integrated circuits, Minuteman II, uses an integrated-circuit guidance computer which, while offering a substantial weight reduction and greater missile range, has about twice the functional capability of the discrete model used in Minuteman I.

In 1967, Arthur D. Little, Inc., published a follow-on report on integrated circuits [17]. It included the following graph showing the preponderance of the military market in the early production of integrated circuits:



Source: Arthur D. Little, Inc.

FIGURE 2 SHIFTS IN INTEGRATED CIRCUIT MARKETS

1966 Ph.D. Dissertation

Dr. Kleiman submitted a dissertation on the integrated circuit in 1966 [15]. His study is of particular value because of its timing (coming shortly after the early use of integrated circuits), because of the thoroughness of his research, and because he had no vested interest in making any particular case. Kleiman described the basis for his study:

> Extensive interviewing supported intensive research on the subject. Interviewees were drawn from industry, the military and space agencies, consulting firms, and academic and financial institutions. The business and technical press were the major sources of documentation for the chronologies of Chapters III and IV. For nearly three years, the author has participated in consulting efforts for various Government agencies relative to the optimum use of the new component. The final analysis and conclusions result from the combination of all three inputs--research, interviews, and author's professional background.

In discussing integrated circuits, Kleiman noted the importance of early military applications:

> The product, then, is one that has found its greatest acceptance in digital applications, first with the military where reliability is critical and, when prices lowered sufficiently, with the makers of industrial computers who are much more cost-conscious.
>
> ...The IC technology, more so than any other innovation in the electronics industry, represents a new approach nurtured and supported by Government funds. It has since been utilized not only in military and space programs, but has "spun off" to many non-Government applications.
>
> ...In Chapter IV, a documentation is presented depicting the sustained interest exhibited in both military and industrial organizations since the inception of the IC development. In the early years of its growth, the new technology has had indispensable support from the military.

Kleiman pointed out the military interest in electronic miniaturization as an important factor in stimulating industry interest in the direction of the integrated circuit:

> The major efforts to miniaturize electronic components and ultimately electronic equipment stem from the military agencies. They not only advocated and needed space savings, but they funded the initial programs aimed at accomplishing the same. Sometimes, small size was not the only objective of a program that might lead to miniaturized components; often, it was not even a primary goal. Still, it was through these efforts that the initial interest in miniaturization was generated.

He then went on to discuss the various service programs in electronic miniaturization:

- Army's auto assembly technique (about 1949)
- Navy's Project Tinkertoy (about 1950-1953)
- Army's Diamond Ordnance Fuze Laboratories 2-D Program (about 1957-1959)
- Army Signal Corps micromodule program (about 1958-1963).

Kleiman included many quotations from the press during these years that stressed the military's need for more reliability in electronics equipment for use in aircraft, missiles, space systems, and ships.

Kleiman then recounted the major events in developing integrated circuits. The excerpts below indicate the heavy military involvement; Kleiman also covers other activities not involving the military that are not included below:

> Before the spring of 1959, references to this new technology were sparse. In April of that year, when the first contract for molecular electronics was let, the rumblings increased in volume, spurred on by the participation of the military....The Air Force introduced a new technology called molecular electronics which had gained adherents within that agency. Its impact would be radical, it was prophesized:
>
> > Molecular circuitry may upset traditional lines of demarcation between electronic component and equipment manufacturers. Because molecular circuitry poses a direct threat to conventional parts, it is logical to expect more component manufacturers to move to protect

their position. However, molecular circuitry will require much more research and knowhow than many of the smaller component manufacturers now possess.[7]

The Air Force, after considerable review on its own part, was seemingly prepared to sponsor work in this particular field of research.

By late 1958, molecular electronics was being touted as the needed technology for future space vehicles and weapon systems. The practical utility forthcoming from devices and systems using this new technology, it was suggested, would be dependent upon how fast military and industrial management accepted the value of molecular electronics.[9]

...In April, 1959, the long-awaited first molecular electronics contract was released by Air Research and Development Center (ARDC) of the Air Force. The aim of this $2 million effort was to develop a fundamentally new approach to avionic equipment design and fabrication of electronic equipment, structured upon basic building blocks.

...During the length of the two-year contract, Westinghouse in the first year would deliver eight circuits demonstrating the new technology, and the second half of the effort would be devoted to investigating the feasibility of components for representative Air Force equipments.

...The contract represented the initial thrust by the Air Force in its molecular electronics program. It triggered an avalanche of activity and soul-searching for the semiconductor components industry. The first flurry of attention was followed by an intensive campaign to insure its continuance.

...In short order, the industry began to heed the message:

> Interest and activity in molectronics and microcircuitry is spreading through the avionics industry, sparked by the needs of space and missile technology and by a recent major program launched by the Air Force at Westinghouse Electric Corporation.

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[7]Philip Klass, "Electrochemistry May Cut Circuit Size," *Aviation Week*, June 2, 1958, p. 66.

[9]Charles Wendel, "Molecular Field Seen Key to Space," *Electronic News*, November 17, 1958, p.5.

> At least 20 companies, ranging in size from the the giants to the smallest, from semiconductor and component makers to equipment manufacturers, are actively engaged in molectronic research and in related micro-circuitry development.[13]

...Emphasized by the intent of Electronic Technology Laboratory of Wright Air Development Center, Air Force interest lay squarely with molecular electronics and not with conventional techniques; its strong support in this area was clear.[17]

...Like it or not, the industry was on the edge of an upheaval. Earlier, in May, a high official in DOD had commented:

> Development and military application of molecular electronics will be on a considerably shorter time scale than the transistor.[19]

The industry was being forced to reexamine its techniques, materials, and production methods. The technology was acclaimed not only as an asset for military and space systems but for the whole electronics industry as well.

The momentum was maintained into the new year--1961--as the armed services planned to exploit the various microelectronic technologies. Several programs by the Army and Air Force were described documenting their particular interest areas and the planned allocations in each. The total expenditure outlay for the military for microelectronics, including the Micromodule program, was over $20 million.[20]

...At this time, the Air Force was seeking firms willing to put some of their own funds into new molecular electronics programs. They found one in Motorola which entered into a $1.5 million cost-sharing contract with the Air Force; the company would contribute $0.5 million to the program's work effort.

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[13]Philip Klass, "Space Needs Spur Molelectronics Activity," *Aviation Week*, September 28, 1959, p.73.

[17]"WADC Stresses Moletronics," *Electronic News*, Sec. 1, March 24, 1960, p.96.

[19]J. Bridges, DDR&E, as quoted in "Views Split on 'When' of Molectronics Usage," *Electronic News*, May 9, 1960, p.5.

[20]Barry Miller, "Microelectronics Studies Gain Support," *Aviation Week*, January 23, 1961, p.99.

One company, Westinghouse, was already looking past the immediate military market and predicting the penetration of the consumer sectors with its molecular electronic circuits. Large volumes of these components would allow unit prices to become competitive and then be incorporated into consumer products, it was asserted. Although these claims were met with skepticism in some areas, it indicated that the firm was looking for a broad application for molecular circuitry.

...The Navy was also showing interest in microelectronics. Early in 1961, the Bureau of Ships established a program to investigate the potential of microelectronic circuitry. The project was to combine both in-house and outside contracts; the bulk of the dollars would be devoted to electronic firms in the field.

A major contract was awarded to IBM by the Navy to build a high-volume thin-film production facility--the first of its kind to use thin-film techniques for automatic fabrication of advanced electronic components. In December, an all-Navy panel recommended a sharp increase in the Navy's fundings on microelectronics, with major emphasis on thin-film techniques. The program would aim to supply hardware to users capable of maintaining the new equipment. There was to be no duplication of Army and Air Force work in these areas.

...The IC movement was given great impetus in mid-1962. The Air Force, through the Aeronautical Systems Division (ASD), devised a comprehensive plan to incorporate molecular electronic circuitry across-the-board into systems, sub-systems, and support equipment.

> Molecular electronics, which has been playing a hopeful understudy for several years will be elevated to stardom in ASD programs over the next three years.[25]

ASD felt that current techniques had advanced sufficiently that great improvements in size, weight, and reliability could be achieved. A multi-million dollar program was envisioned translating the molecular electronics technology from promise to reality. The plan that took shape pinpointed two dozen areas in which the Air Force could take advantage of the new technology:

> We feel the Air Force has to go this way and that it can really get some profitable use of the technology right now.[26]

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[25]J. O'Connor, "ASD Programs to Develop Molecular Electronics Use," *Electronic News,* July 16, 1962, p.l.

[26]E. Cooper, ASD, as quoted in J. O'Connor, "Integrated Circuit gets $ Impetus," *Electronic News,* September 24, 1962, p.l.

A $40 million annual boost for molecular electronic expenditures was to be recommended, and the $10 million current level of support for research in this area would probably be maintained.

The ASD backing, still tentative at that time relative to its funding level outlays, contrasted with the announcement in December, 1962, that North American's Autonetics division had decided to use integrated circuits in the Improved Minuteman, WS-133B. Autonetics was a prime contractor to Ballistics System Division, a sister group to ASD. This move had been rumored earlier in the year by industry sources. It was felt that if this high-reliability program did turn to integrated circuits to attain its objectives, it would be a tremendous boost for the IC industry. Two contracts were let to IC suppliers with more to come. Texas Instruments received initial funding of about $1 million, and Westinghouse was awarded a contract of lesser magnitude. For both firms, it was the largest IC order each had ever received.

Besides the programs mentioned above, other applications were appearing. NASA would use integrated circuits in a telemetry system for its Eccentric Geophysical Observatory (EGO). A prototype guidance computer using the new components was in development at AC Spark Plug Division; its possible application would be in a rocket-launched space vehicle. The Martin Company had already designed a digital computer using the IC devices with the hope of incorporating the new equipment into its Titan programs.

The Navy was also accelerating its interest in the microelectronics technology. One high Navy official said that this technology appears to hold "the promise of an ideal [for the Navy, and offers] just about everything we do not have but want."[27] This thought was echoed by a BuWeps official:

> Microelectronics offers us a solution to our problems, and this is the way we are going to go.[28]

The Navy was pushing ahead with its own programs to incorporate various microelectronic components into hardware being produced by its contractors. At the outset, replacement would be piecemeal wherever the new

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[27]Rear Adm. B. F. Roeder, as quoted in "Microelectronics Seen Answer to Navy Needs," *Electronic News*, October 1, 1962, p.4.

[28]Col. A. D. Lowell, Chief, Avionics Division, BuWeps, as quoted in Nilo Lindgren "Navy to Push Microelectronics Development Program," *Electronics*, October 12, 1962, p.24.

devices could be used without incurring an increase in contract cost. A more comprehensive program was outlined aimed at utilizing the full potential of the microelectronic technology by designing the new components into military systems on a broad front. This plan was called MEETAT (Maximum improvement in Electronic Effectiveness Through Advanced Techniques).

...Motorola's president indicated the position of his firm:

> We're designing and producing integrated circuits on a custom-built basis for military and OEM (original equipment manufacturers) customers, and the technology is progressing far enough to make production of standard integrated circuits in the next few years appear feasible.[34]

...In the spring of 1963, the Department of Defense directed all the military services to use microelectronic circuits wherever possible. At the same time, it urged NASA to do likewise in order to obtain the high reliability needed for the latter's projects. Somewhat later, a DoD official suggested that 77.1 percent of all military electronic gear will consist of microelectronic circuitry by 1970.[37]

The Air Force continued its strong support for programs in molecular electronics. A $290,000 six-month contract was let to ARINC Research Corporation to extend a state-of-the-art survey which had been started earlier. It was also funding programs directed to the future design and fabrication of integrated circuits using computerized techniques.

Regarding the impact of government support on integrated circuit development, Kleiman offered the following conclusions:

<u>The IC technology eventually would have been developed by the industry on its own</u>.

There is no doubt that there were forces within the industry in the late fifties which would have ultimately induced the introduction and development of the integrated circuit. The most important movement was the forward progress of the semiconductor technology. Combined with the

[34]R. Galvin, President, Motorola, Inc., as quoted in Al Wrigley "Motorola Semicon Volume Rises 25-50% for 3d Year," *Electronic News*, March 18, 1963, p.80.

[37]"Micro Gear to Dominate: Defense Aide," *Electronic News*, September 30, 1963, p.29.

industry's affinity for rapid change, the desire for growth products, and the nature of the men who were the major protagonists, the technological progress allowed for and urged the creation of a new electronic component. It was, to some degree, an idea whose time had come.

The major IC advances were not attributable to Government support.

The important technological innovations associated with today's IC product were not achieved as the result of the Government-funded R&D programs; one could almost argue that they occurred in spite of them. The major advances were generated by the in-house internally-funded projects of private firms. However else the Government may have contributed to the continuing development of the IC component, its formal R&D programs were not the source of the critical breakthroughs.

The major Government contribution in advancing the IC technology was the establishment of a "conducive climate."

The Government's main contribution to the introduction and development of the IC component lay in its ability to "fertilize the ground" rather than "plant the seed." The various Government agencies by their insistent demand for electronic components that were more reliable and smaller continually maintained a pressure on the industry to move toward these goals. The military services and NASA created an atmosphere of urgency which carried a double meaning. For those firms who could develop the desired devices, the Government would be a very obvious first customer; for those who did not generate improved components, the Government might not be a customer at all. With NASA, the message took on an air of national importance which could not wholly be translated into pecuniary motivation. This "carrot and stick" theme had its effects both on the components and systems houses and especially upon those companies that greatly relied upon military procurement for their livelihood. For a firm less dependent upon the military and NASA as a purchaser, it saw a first customer willing to pay the higher initial prices--assuming the right product could be developed--that would facilitate the offering of a product line to non-military, non-space clientele.

The Government accelerated the development of the IC component.

The Government role as R&D sponsor greatly accelerated the oncoming of the IC device; as stated above, it did not initiate the movement in that direction. By its dollar support of R&D projects for IC improvements it reinforced in very tangible specific terms what it had been advocating in a more general way: the Government is interested in improved electronic components offering particular advantages. Most probably, the initial contract efforts could not have been funded except on a "cash-on-the-barrelhead" basis, and even this approach had limited or no attractiveness for some firms. The Air Force, however, was willing to back up its words with direct dollar support. This policy not only stimulated the companies contracted to continue in this direction, but it had a similar effect on the others who either could not or would not obtain R&D contract awards. In such a manner, the Government accomplished one of its major objectives: it "persuaded" the industry to allocate its own funds toward the same goals. Although impossible to quantify, the industry has most definitely spent a great deal more for IC development than the Government. This has been one of the Government's prominent contributions to the IC cause: its expenditures have induced even greater outlays by the industry itself thereby creating a multiplying effect. The combination of heavy R&D spending and the attendant publicity constituted a steamroller mechanism which the industry found difficult to ignore; it wouldn't and couldn't.

The Government failed in its initial intent relative to molecular electronics.

Molecular electronics, the original goal of the Air Force contracts, is probably as significant in the market place today as it was seven years ago. As emphasized previously, today's IC component is far removed from the hoped-for molecular electronic device of yesterday. If the Government programs were helpful in other respects, they were fruitless in developing the molecular electronics concept and translating it into useful products. If the term is still used in today's parlance, it should refer to a potential development of the IC future. The present IC concept is not a result of Government funding--development, yes; conception, no.

New product lines for industrial-consumer applications are sometimes dependent upon the existence and success of the component lines offered to the various military and space agencies.

Although the function per se of Government research and procurement is not to facilitate the offering of new product lines for industrial-consumer applications, the dependence is often great upon Government participation with respect to the appearance of new electronic components. If the Government had not sponsored the original R&D contracts for IC programs or if the military had been less enthusiastic in its statements, the IC component would still have eventually been developed. If the Government however, had not been the initial customer willing to buy high-priced products, the previous conclusion is in much greater doubt. The Government is considered by many to be the means by which certain non-Government markets are penetrated. The present low-cost IC lines probably would not have been available had this condition--Government purchases--not prevailed. In turn, once the firm can cater to the non-Government market, there are salutary returns for the military-space products being offered; lower prices and better quality may be forthcoming.

1968 Organization for Economic Co-operation and Development (OECD) Study

A 1968 study by the OECD [1] discusses the important role played by the U.S. Government, and particularly DoD, in bringing the U.S. semiconductor industry to its position of preeminence on the world scene:

> ...it is apparent that the world market for advanced semiconductor components is dominated by the United States, a situation which is linked with the widespread demand for technologically sophisticated products resulting in part from the high level of income. This situation is strongly reinforced by the United States Government market for components which is in general considerable....
>
> ...Markets have been substantially influenced on the American scene but less so elsewhere, by defence and space goals. Massive programmes of research, development and pilot production, with clearly defined goals and powerful means at their disposal, constitute a stimulus and an aid to industry which may be of crucial importance in forcing new technologies through the initial stages of development faster than would otherwise be possible. In this connection, it should be noted that the methods of United States Government support are as important as their scale, in that the United States support in this sector is concentrated in industry rather than in Universities and Government laboratories. Such methods facilitate the transfer of the results of Government supported R & D into the economy.

Italics have been added to the following material from the OECD study to highlight the portions dealing with DoD support of integrated circuit development:

> Two major decisions relating to the electronic components industry were taken at that time. In 1956, the US Department of Defense gave major production contracts for transistors to twelve firms, and *in 1958 the Air Force decided to launch a large scale R & D effort into what was then called "molecular electronics", and was later developed under the more familiar name of "integrated circuits"*. This is not to say that Government support started in 1956 or 1958; in fact military interests in the electronics industry are as old as the industry itself, and a number of important projects had been going on since the end of World War II. The two dates above do not mark any fundamental revolution, but they can retrospectively be considered to have marked a considerable increase in the support given to a specific sector of the American electronics industry, and consequently an acceleration of the pace of technological change.
>
> No precise data are available on the total sums of money channelled into the semiconductor industry (integrated circuits not included). The major contracts given out in 1956 called for an expenditure of approximately $40 million over a three-year period, and it appears that these three years marked a peak. Sums funded out between 1952 and 1956 are probably smaller; and *after 1960, it is known that the greatest emphasis was put on integrated circuits.*
>
> *For the integrated circuit sector, total Government funding for research and development alone exceeded $100 million between 1959 and 1965.*[1] If we remember that in 1959 and 1960 total contracts were below the $10 million mark, this means that the average yearly expenditure in the five following years must have been around $18 million.
>
> The major difference between semiconductors and integrated circuits is that in the case of the latter, the effort was much more highly concentrated, both in terms of number of firms involved and in terms of length of time. Moreover, *Government support of the integrated circuit industry started very soon after*

[1] "The Employment Impact of Technological Change." Appendix Volume II. Studies prepared for the National Commission on Technology, Automation and Economic Progress. Washington DC, 1966.

the first developments were made (around 1959-1960), whereas in the semiconductor industry it started a few years after the main developments had been made (around 1952, i.e. 4 years after the transistor was announced).

The OECD study included an interesting summary of key events in the development of integrated circuits:

The first idea of the integrated circuit was formulated in 1952[1], and an attempt by some United States Air Force scientists to get the Department of Defense interested was made unsuccessfully in 1953. Four years later, it was becoming increasingly obvious that the future requirements of military electronics could not be solved through any of the approaches currently under development (notably the thin-film technology sponsored by the Navy and the micro-module technology sponsored by the Signal Corps); consequently the Air Force decided to launch a large scale effort in molecular electronics. The only favourable response from the industrial community came from Westinghouse, who subsequently received two major contracts. Practically at the same time (1958) Texas Instruments developed with its own money the first integrated circuit in the United States[2]. In 1959, a first Air Force contract was given to Texas Instruments, and a second followed late in 1960. Total contracts to Texas Instruments and Westinghouse during these three formative years amounted to a little over $5 million.

In the development phase, Government support was largely directed towards the development of various pieces of equipment using integrated circuits. The primary aim of these programmes was not to create equipment directly usable by the military customer, but rather to gain a thorough knowledge of how IC's could be put to work in electronic systems and to convince companies and other Government agencies that these new systems were more reliable and much less cumbersome than their predecessors.

Although this development work proved extremely useful both to the Department of Defense and to the companies involved (mainly Texas Instruments and Westinghouse), it is doubtful whether IC's would have

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[1]by G.W.A. Dummer of the Royal Radar Establishment, in a conference given in Washington.

[2]The first working model of an integrated circuit was developed by Plessey, a British firm, in 1957.

meant such a far-reaching revolution, had they remained confined to the military market, or to certain very specialised applications in the industrial market: from an economic point of view, the real impact of IC's was to come only a few years later, with mass production, falling prices and, consequently, an increasing pervasiveness of electronics in the whole fabric of the economy.

The major step in this breakthrough was made in 1960-61 with the invention of the planar process by Fairchild's three year old semiconductor division. The planar process, developed without any Federal support, and subsequently adopted by all IC manufacturers, paved the way to mass production. One can argue that, had Fairchild not existed, some means would have been found of breaking the price barrier[2]. Companies were beginning to realise that IC's would ultimately have to become as cheap as the transistor, and the various efforts undertaken in this direction probably would have borne fruit, although possibly only a few years later. Nevertheless, the fact remains that although very substantial results were achieved through direct Government support, the main breakthrough, after the initial development of Texas Instruments and Westinghouse, was made by a small company without any Government help.

Although the breakthrough was made by a company using its own funds, it must be noted that Fairchild earned the money for developing the planar process by selling high priced prototype devices to the Government for research purposes.

Note in the review above that even in cases where DoD was not directly involved, it still played a supportive role. Following development of the first integrated circuit by Texas Instruments in 1958, the Air Force provided contract support in 1959 and 1960. And the development of the planar process by Fairchild Semiconductor Corporation was at least partially financed by earnings from sales to the Government.

[2]At least two American companies, one in the United States, and the other in the United Kingdom, had developed a process similar to planar before Fairchild, but for various reasons these breakthroughs were never developed commercially.

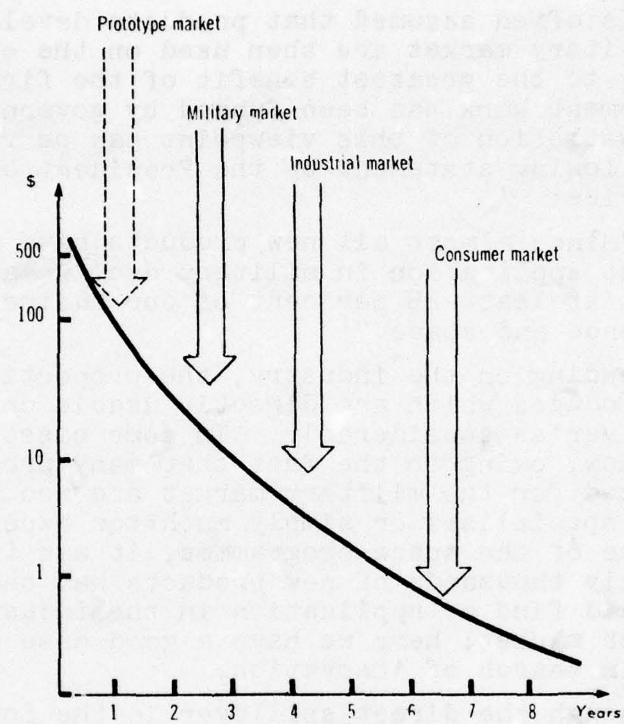
The OECD study then went on to describe the subsequent support of DoD and NASA in providing the early markets for production of integrated circuits:

> ...In 1962, the first major market for IC's was opened up: the Minuteman II missile which was to replace Minuteman I, entered its development phase. The contract given to Texas Instruments by the Autonetics Division of North American Aviation and the Air Force, called for the production of more than 300,000 ICs.
>
> The first market was soon followed by others, both in the military field (e.g. the Phoenix air-to-air missile, or the Navy's Mark 48 torpedo), and in the space programme (IMP satellite, Apollo spacecraft). The importance of these Government contracts was considerable: in 1964, they absorbed over 90 per cent of the industry's output in dollar terms and two years later the figure was still as high as 53 per cent.
>
> The creation of large Government markets for entirely new products like transistors or integrated circuits is of considerable importance in that it provided a strong incentive for the firms involved to develop their technologies and allowed them to overcome within a relatively short period the cost barrier which prices these new products out of the civilian markets.
>
> If a typical cost curve for integrated circuits or transistors is considered, it will be found that in the first years these new products are far too expensive to be sold on the industrial market, let alone on the consumer market. Only when the technology has been fully mastered can these products be widely adopted by industry; this can take a number of years. However, if governments can create a reasonably wide market at the stage when these products are still very expensive, the subsequent price fall can be more rapid and the penetration of the new products into the economy greatly accelerated.
>
> In the case of integrated circuits, a preliminary market was created in the form of government purchases of prototypes. This preliminary market, which occurs only in the case where a government is heavily involved in the R & D stage, can be located in the two or three years preceding the development of the military market. From the viewpoint of the firm, this market can generate substantial income, which will be used for further development.

Chart 4 illustrates summarily the price level at which each of these new markets tends to open up:

Chart 4

UNIT COST AND MARKET PENETRATION



The problem facing firms in countries with no large scale military markets is the following: how can the cost of developing new technologies be borne until they become sufficiently cheap to be adopted by the industrial and the consumer market?

The importance of the early military market is again noted (italics added):

> As for integrated circuits, the present [*1968*] very rapid growth rate can to a large extent be explained by the tremendous expansion of the computer industry; *in 1963-1964, the impetus was coming from another market, namely that for missiles.*

The OECD study then discussed the importance of military R&D in laying the groundwork for later applications in the civilian market:

> The impact of Government support raises three further questions. The first concerns the way in which the transfer of technology from military and space programmes takes place....
>
> It is often assumed that products developed for the military market are then used on the civilian market, to the greatest benefit of the firms whose development work has been funded by government money. An illustration of this viewpoint can be found in the following statement by the President of Litton Industries:
>
> > "Since almost all new products have their first application in military use, we always want at least 25 per cent of our business in defence and space."[1]
>
> Depending on the industry, the proportion of military products which are directly usable on the civilian market varies considerably. In some cases it may be quite low, owing to the fact that many products developed for the military market are too complex, too highly specialised or simply much too expensive. In the case of the space programmes, it was found that literally thousands of new products had been developed, but could find no application in the industrial or consumer market; here we have a good case of inventions in search of innovation.
>
> Although the direct spillover in the form of products is important, the indirect spillover in the form of technology and know-how may in many instances be even more important. The benefit of a contract is that it allows a firm to develop a capability in a particular field, to explore new fields which will some day prove useful and to enlarge its overall technological capability. The following "technology tree" (Chart 5) summarises the two types of spillover, at the product level and at the technology level.

The relative widths of the arrows indicate that technology transfer is thought to be considerably more important than product transfer.

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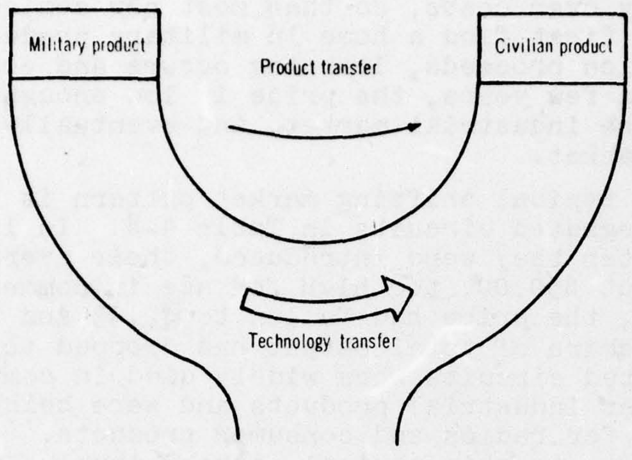
[1]"Management Today", October, 1967.

Chart 5

PRODUCT AND TECHNOLOGY SPILLOVER



1971 Brookings Institution Book

Tilton [2] noted the primacy of the military market in the early days of integrated circuits:

> When this new device was first introduced into the market, it was expensive compared to the discrete semiconductors it could replace and so was used almost exclusively in government equipment, particularly in missiles where performance, not cost, had top priority.

Tilton discussed the importance of military demand on the semiconductor industry as a whole and on the integrated circuit portion of the industry:

> The importance of the defense market for semiconductors is shown in Table 4-7. This market grew from $15 million in 1955 to $294 million in 1968 and, depending on the year, accounted for between one-fourth and one-half of the total market.
>
> The impact of military demand on the semiconductor industry transcends its size. The armed forces have always imposed the most rigid standards and quality control. They have constantly demanded better devices and have not hesitated to inform the industry of specific needs. Moreover, they provide a substantial market for new devices that meet their requirements.

The latter is particularly important. Often new and better semiconductors are initially too expensive for industrial or consumer electronic products. In military equipment, reliability and performance have priority over costs, so that most new semiconductor devices first find a home in military products. As production proceeds, learning occurs and costs fall. Within a few years, the price is low enough to penetrate the industrial market, and eventually the consumer market.

This typical shifting market pattern is illustrated for integrated circuits in Table 4-8. In 1962, the year after they were introduced, their average price was about $50.00, too high for use in commercial products. By 1968, the price had fallen to $2.33 and the military's share of total output had dropped to 37 percent.[50] Integrated circuits were widely used in computers and other industrial products and were being considered for radios and consumer products.[51] The few exceptions to this typical pattern involve primarily new semiconductors whose virtue is lower costs rather than improved reliability or greater capabilities. One example is plastic-encapsulated devices, which the armed forces have hesitated to accept for fear they will prove less reliable than devices using the conventional and more expensive seals. Generally, however, it is the military that first uses new semiconductors and provides the immediate incentive for firms to develop them.

The defense market has been particularly important for new firms. For reasons noted in the previous section, these firms often have started by introducing new products and concentrating in new semiconductor fields where the military has usually provided the major or only market. Fortunately for them, the armed forces have not hesitated to buy from new and untried firms. In early 1953, for example, before Transitron had made any significant sales, the

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[50]Some of the price decrease, of course, was caused by (rather than being the cause of) the increase in relative importance of the commercial market, which does not demand as high performance standards as the military market.

[51]For a brief description of how this shifting market pattern evolved for the surface-barrier transistor, see David Allison, "The Civilian Technology Lag," *International Science and Technology* (December 1963), p.30. For more general information on shifting market pattern in the semiconductor industry, see OECD, *Electronic Components: Gaps in Technology*, pp.62-65.

Table 4-7. U.S. Production of Semiconductors for Defense Requirements, 1955–68[a]

Year	*Total semiconductor production (millions of dollars)*	*Defense semiconductor production[b] (millions of dollars)*	*Defense as a percentage of total*
1955	40	15	*38*
1956	90	32	*36*
1957	151	54	*36*
1958	210	81	*39*
1959	396	180	*45*
1960	542	258	*48*
1961	565	222	*39*
1962	575	223	*39*
1963	610	211	*35*
1964	676	192	*28*
1965	884	247	*28*
1966	1,123	298	*27*
1967	1,107	303	*27*
1968	1,159	294	*25*

Sources: Data for discrete devices are from U.S. Department of Commerce, Business and Defense Services Administration (BDSA), *Electronic Components: Production and Related Data, 1952-1959* (1960); BDSA, "Consolidated Tabulation: Shipments of Selected Electronic Components" (annual reports; processed; title varied somewhat over the period).

a. The 1962-68 data include monolithic integrated circuits. Figures on the latter are as shown in Table 4-8 and come from the sources given there.

b. Defense production includes devices produced for Department of Defense (DOD), Atomic Energy Commission (AEC), Central Intelligence Agency (CIA), Federal Aviation Agency (FAA), and National Aeronautics and Space Administration (NASA) equipment.

Table 4-8.[1] U.S. Integrated-Circuit Production and Prices, and the Importance of the Defense Market, 1962–68

Year	*Total production (millions of dollars)*	*Average price per integrated circuit (dollars)*	*Defense production as a percentage of total production[a]*
1962	4[b]	50.00[b]	*100[b]*
1963	16	31.60	*94[b]*
1964	41	18.50	*85[b]*
1965	79	8.33	*72*
1966	148	5.05	*53*
1967	228	3.32	*43*
1968	312	2.33	*37*

Sources: Total production and average price figures are from the *Electronic Industries Yearbook, 1969* (Washington: Electronic Industries Association, 1969), Table 55. Defense production as a percentage of total production is based on data for monolithic integrated circuits found in BDSA, "Consolidated Tabulation: Shipments of Selected Electronic Components."

a. Defense production includes devices produced for DOD, AEC, CIA, FAA, and NASA equipment.

b. Estimated.

[1]It should be noted that the figures of Tilton's Table 4-8 are for monolithic integrated circuits only; the DoD percentage of all integrated circuits was considerably lower. However, monolithic integrated circuits offer the greatest potential for improvement over the previous generation of discrete semiconductor components.

military authorized the use of its gold-bonded diode. This approval has been called the real turning point for the new firm.[52] During 1959, new firms accounted for 63 percent of all semiconductor sales and 69 percent of military sales.[53]

Military demand has therefore stimulated the formation of new companies and encouraged them to develop new semiconductors by promising the successful ones a large market at high prices and good profits. Further, the military market, by activating learning economies, often serves as a stepping stone to eventual penetration into the commercial market.

Tilton presented data on U.S. Government support for semiconductor R&D:

Direct government funding for R&D and production refinement projects is shown in Table 4-9 for 1955-61. Support for R&D accounted for more than half the funds for the period as a whole and increased substantially. A large part of the money for refinement projects came in 1956 when $14 million was appropriated for transistors. Contracts placed with about a dozen firms called for the delivery of some thirty different types of germanium and silicon transistors over the following several years. In addition, for each type, production lines capable of turning out 3,000 units a month were to be developed. While the companies paid for plant facilities, the government covered engineering design and development. This support helped firms get into the industry and greatly expanded semiconductor production capacity in the United States. Funds for diodes and rectifiers, though more modest, also contributed to this capacity.

The Department of Defense conducted a special survey in 1960 to determine the total amount of semiconductor R&D financed directly as well as indirectly by the government through its expenditures on weapon systems. It found $13.9 million had been spent in 1958 and $16.2 million in 1959[55]--according to Table 4-9, more than double the amount the government funded directly through R&D contracts.

The survey also revealed that government-sponsored R&D has constituted a large part of the total in the

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[52]Harris, "The Company That Started with a Gold Whisker," p.140.

[53]See Table 4-10 and source [Source: U.S. Department of Defense, Survey of 64 Semiconductor Companies, 1960, unpublished tabulations].

[55]BDSA, *Semiconductors: U.S. Production and Trade,* Table 9.

Table 4-9. U.S. Government Funds Allocated Directly to Firms for Semiconductor Research and Development and for Production Refinement Projects, 1955–61

Use of funds	*1955*	*1956*	*1957*	*1958*	*1959*	*1960*	*1961*
Research and development	3.2	4.1	3.8	4.0	6.3	6.8	11.0
Production refinement							
Transistors	2.7	14.0	0.0	1.9	1.0	0.0	1.7
Diodes and rectifiers	2.2	0.8	0.5	0.2	0.0	1.1	0.8
Total	8.1	18.9	4.3	6.1	7.3	7.9	13.5

Source: BDSA, *Semiconductors: U.S. Production and Trade* (1961), Table 8.

semiconductor industry--25 percent in 1958 and 23 percent in 1959.[56] Such support is almost entirely for R&D on military requirements and directly helps recipient firms expand their military sales--an important consideration in an industry where the military accounts for between 25 and 50 percent of the total market.

Government R&D funds also help companies in the commercial market. Indeed, there is some evidence suggesting that the spillover may be substantial....Although conflicting with much of the prevailing opinion about the importance of spillover in general, the existence of considerable spillover in the semiconductor industry is not surprising, since similar technology is used to produce both military and commercial devices and modified versions of many devices initially used in military equipment are eventually used in industrial and consumer equipment too.[57]

Tilton then discussed the importance of government R&D relative to procurement in stimulating the growth of the semiconductor industry (italics added):

...This raises an important policy question: How important has government R&D funding been compared with government procurement in stimulating the growth and technological development of the semiconductor industry in the United States? *Though evidence is*

[56]*Ibid.*

[57]Although they maintain that spillover in general is not important, Nelson, Peck, and Kalachek do point out that it may be significant in certain fields and specifically mention components as a possibility. See Richard R. Nelson, Merton J. Peck, and Edward D. Kalachek, *Technology, Economic Growth, and Public Policy* (Brookings Institution, 1967), pp.82-85.

limited, government procurement has probably had a much greater effect. As the tables of this section indicate, the defense market has pumped many more dollars into the industry than the government has in supporting R&D and production facilities. Moreover, many of the major semiconductor innovations were achieved by firms without any government assistance. Bell Laboratories produced the first transistor with its own funds. And despite the many millions of R&D dollars the Air Force spent to develop integrated circuits, company-financed R&D projects produced the major breakthroughs.[59] Only after Texas Instruments achieved a working model of an integrated circuit did it receive an Air Force contract for subsequent development. And Fairchild developed the planar process, which led to the mass production of integrated circuits, without any government support.

Tilton presented the following conclusions on the role of government in the semiconductor industry:

> ...The large defense market for semiconductors, which accounts for a significant segment of the overall market, appears to have played a more important role in fostering the industry's growth and technological development. It demands the best quality semiconductors. It offers the financial incentives that stimulate the development of better devices for defense equipment, and eventually for commercial products as well, for in filling military orders learning economies arise and reduce costs. The defense market is particularly important for new firms hoping to introduce new semiconductor devices and has facilitated their entry.

1971 Ph.D. Dissertation

In 1971 A.M. Golding, a Britisher, submitted a dissertation on the semiconductor industry in Britain and the U.S. [3]. In doing his research, Golding spent four months in 1969 in the U.S., during which time he interviewed many people in the semiconductor industry. He noted that his study

> ...relies for much of its data input on material which is not available in published form. More especially, it is extensively based on information

[59]See Kleinman, "The Integrated Circuit," pp.172-215; OECD, *Electronic Components: Gaps in Technology,* Chap. 4.

> gathered in the course of interviews with over one hundred personnel employed in, or associated with, the semiconductor industry, both in Britain and the United States of America.

Golding included considerable material on the development of integrated circuits. Because of his thorough research, and the fact that he is a foreigner with no direct participation in these events, his views are of particular interest.

In his dissertation, Golding noted the important role played by the U.S. military services in the development of integrated circuits:

> The primary impetus for microelectronics has been provided by the three military services in the U.S.A.

Golding included a history of U.S. semiconductor firms. His review of Texas Instruments (TI) notes the importance placed by TI on the military market (see italics added). Although Kilby of TI developed the first working integrated circuit with company funds, the profits, facilities, and personnel associated with military products undoubtedly indirectly supported Kilby in his work:

> The firm traces its pedigree back to 1930 when Geophysical Service Inc. was incorporated to carry out oil exploration surveys under contract.[6] Between 1941-45, *GSI moved into naval contract work on a small scale and, after the war, the firm decided to expand in this direction in an effort to avoid the vagaries of the geophysical service business. GSI expressed an intention of becoming a major manufacturer of military electronic equipment from an initial base as a second source supplier. By 1950, military contract awards had reduced the dependence on geophysical exploration to about one half of total sales,* amounting to $7.6 m., and the name of the firm was subsequently changed to Texas Instruments (hereafter referred to as TI). Perceiving an opportunity in the embryo semiconductor field, TI sought throughout 1951 to obtain a license but was forced to wait until the first (Technology)

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[6]A detailed history of the company may be found in John McDonald, "The Men Who Made T.I.", *Fortune*, Vol. 64 (November, 1961). p.116 ff.

Symposium in the Spring of 1952. TI adopted a three pronged product strategy. *The first aspect involved the setting up of a solid-state R & D laboratory (now the Central Research Laboratory) with the achievement of a transistor suitable for military application as its initial objective.*[7]

...Although the company subsequently expanded from its initial military base into commercial markets, it retains a marked orientation towards government business.

Texas Instruments has been prominent in the development and exploitation of IC's. For a time, it lost the initiative in the commercial market to Fairchild but a vigorous counter-attack since 1966 with Series 54/74 TTL has enabled it to regain much ground in this rapidly expanding sector. This serves to illustrate one aspect of the TI policy: Fairchild was able to take the lead in the commercial field *because of a preoccupation at TI with the higher priced military/space outlets.* Indeed, the firm has acquired a reputation for pursuing a skimming policy in an effort to maintain the innovation premium for as long a time as possible. *Such a policy is necessarily aimed at the government user.*

Golding noted military involvement with Westinghouse Electric in both R & D and production (italics added):

This large electrical engineering firm began the development of silicon power devices in 1952. Despite efforts to penetrate lower power markets, Westinghouse remained primarily a supplier of power semiconductors for electrical engineering applications throughout the 1950's. According to one analysis, it was this lack-lustre performance in the lower power sector which encouraged the firm to seek a "quantum jump" into a (potentially) revolutionary technology *through the medium of a major molecular electronics contract with the U.S. Air Force.*[20] When, in 1962, the superiority of planar IC technology had been proven beyond doubt, Westinghouse decided to convert to these techniques. Subsequently, the newly-formed Molecular Electronics Division constructed a facility to manufacture IC's for commerical markets. *(The Westinghouse Air Arm Division, in which the original molecular electronics R & D was conducted, retained responsibility*

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[7]It is interesting to note that the laboratory spent a total of $60,000 in its first year of operation and $190,000 during 1954.

[20]Kleiman, p.186.

for military/space IC production while the manufacture of discrete components continued in a separate Semiconductor Products Division.)

Golding also mentioned RCA's military business:

> Between 1958 and 1964, RCA was the prime contractor to the U.S. Army Signal Corps for a very substantial program involving the development and manufacture of micromolule assemblies. Partly as a result of this major commitment, RCA's entry into quantity production of silicon planar devices was delayed until 1964. Approximately one-half of the current IC output consists of linear circuits for use in consumer and industrial equipment.

Golding discussed Transitron's heavy orientation toward the military market and speculated that over-reliance on the military market may have been harmful in the long run:

> Founded by the two Bakalar brothers in August, 1952, Transitron enjoyed spectacular success in the 1950's. Sales rose from $10,000 in 1953, to $42 m. in the year ending June, 1960, yielding a net profit of $6 m. Though second in terms of sales to Texas Instruments, Transitron was considered as the more profitable in terms of return on invested capital. (A strict comparison is not possible as the TI accounts do not reveal the profitability of the semiconductor segment of the whole.) The emphasis was on volume production with an orientation towards government markets. ...A further factor in the post-1960 decline may have been an undue reliance on military purchases; government business accounted for about sixth percent of sales in 1960.[24] Unlike the majority of its competitors, Transitron had made little attempt to penetrate commercial markets.

Golding devoted an entire chapter to "The Role of Government" in the development of the American and British semiconductor industries. He opened with a review of the literature dealing with the general subject of spin-offs of U.S. Government defense/space programs into the civilian economy. The consensus of the literature on this subject is that there are significant

[24]"Company Profile: Transitron Electronics Corporation", *Solid-State Journal*, Vol. 2 (March, 1961), p.54.

spinoffs. However, they are mainly in the form of new products resulting from defense/space technology rather than direct transfer of products themselves. It is also believed that the early production market provided by the government for advanced technology products is at least as important in fostering spinoffs as is direct R & D funding by the government.

Golding's paper included a thorough review of the role of the U.S. Government in integrated circuit development. Because of their direct pertinence to the subject of our study, these sections of Golding's paper are reproduced in full. Italics have been added to statements of particular interest. Note Golding's conclusions in the final paragraph below (numbering system is Golding's):

10.2.2 The Influence of Government on Integrated Circuit Development

The trend towards miniaturisation of electronic circuitry began as a reaction against the gross dimensions of the cumbersome vacuum valve [tube]. *Much of the stimulus for the development of smaller circuitry came from the Armed Forces.* In the late 'forties, the Army attempted to achieve smaller size electronic equipment through an improved manufacturing technique for conventional components. This idea was subsequently adopted by the U.S. Navy for "Project Tinkertoy", a mechanised production method in which the emphasis was placed on ease of manufacture and cost reduction rather than miniaturisation. The Navy was singularly unfortunate in that the emergence of Tinkertoy as a viable production process coincided with large-scale military support for the transistor. In 1958, the Army Signal Corps initiated a programme with RCA as prime contractor for the mechanised manufacture of compact modules. This micromodule concept was directly descended from the original Tinkertoy project with one significant change: the substitution of transistors for valves. Between 1958 and 1964 RCA received production contracts approaching twenty-six million dollars in value.

The expressed desire of the three Armed Service branches for improved circuitry generated much interest in the latter part of the 'fifties in a wide variety of microelectronic techniques. However, the precise needs of each of the three services necessarily differed according to their prevailing operational conditions. The Air Force, in particular, was faced with an acute tyranny of numbers problem. System reliability continued to show a significant decline as the complexity of airborne equipment increased at an exponential rate.[20] It was evident that improvement in circuit reliability would produce multiple benefits....Above all, it would lift the ever-present threat to the performance of its operational role. At the same time, enhanced reliability would produce cost savings over the entire cost-of-ownership. *The molecular electronics concept was evolved in an Air Force laboratory as a direct response to this need for a step function improvement in reliability. In 1959, Westinghouse Electric (which was already pursuing a similar line of enquiry) accepted the award of a $2 m. contract to investigate the feasibility of molecular electronics.* The two remaining Armed Services meanwhile continued to pursue independent paths towards the elusive microelectronics goal. The Navy favoured thin film hybrid concepts while the Army engaged in some in-house thick film work as well as providing sponsorship for the micromodule programme at RCA.

The interest registered by the military in microelectronic techniques soon communicated itself to the electronics industry at large and widespread activity resulted. All firms perceived the potential for increased business with government customers. Investigation was widely distributed throughout the electronics industry and not confined to semiconductor companies. Much of this effort relied on the extension of well-understood existing technology, in the form of discrete component packaging schemes, and was not orientated towards the search for an IC per se. An enquiry carried out at the end of 1962[21] underlines the degree of commitment to discrete packaging techniques even at this comparatively late stage in the evolution of the IC. Out of a total of fifty-nine electronics companies surveyed, thirty-five were engaged in some kind of modular packaging exercise. Thirty-four firms indicated an interest in film technology while only fifteen were actively pursuing a semiconductor approach. (There was a considerable overlap between the last two categories, many concerns being involved

[20] Well illustrated by the twelvefold increase in the number of active components used in the B-17 and B-58 bomber aircraft (spanning a period from 1941 to 1958). Air Force Systems Command, p.3.

[21] "Microelectronics Today", Electronic Industries, December, 1962, pp.92-99.

in both, which explains why the aggregated figure does not tally with the original total.)

During late 1958 and early 1959 Texas Instruments presented briefings and demonstrations of working integrated circuits, based on the original insight of J.S. Kilby, to the Air Force Research and Development Command and other government agencies. The company accepted an Air Force development contract in June, 1959. This was soon followed by a second contract, valued at approximately $2.8 m., calling for the immediate construction of a small digital IC computer and the refinement of production techniques. (It included the setting up of a pilot assembly line capable of fabricating five hundred IC's a day for ten consecutive days.) *The successful completion of the project convinced the Air Force of the benefits to be derived from the IC approach and it immediately commissioned TI to build a second apparatus involving the substitution of integrated circuitry in an existing item of transistorised equipment. Westinghouse Electric received parallel contracts totalling $4.3 m. for two further integrated equipments utilising modified molecular electronics techniques. The objective in all three cases was to demonstrate the feasibility of incorporating IC components in actual equipment to system manufacturers and users.* The construction of these three demonstration vehicles during 1961 coincided with the introduction of TI's Series 51 family of circuits, developed partly with support from the National Aeronautics and Space Administration (NASA). Westinghouse Electric too announced its intention of entering the commercial market with a range of ICs based on technology generated by its molecular electronics contracts but was soon forced to convert to the superior planar techniques employed by Texas Instruments and Fairchild.[22]

While several other semiconductor companies received Air Force contracts for the advancement of IC technology, only Motorola became involved in a major programme. It negotiated a $2 m. award for a broad-based investigation with the ultimate objective of combining thin film and semiconductor technologies

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[22]See chapter 6.2.5. The molecular electronics programme at Westinghouse was based on processes which were used primarily for manufacturing high-power discrete devices. Unlike the planar-diffusion approach this method was not amenable to batch processing. Westinghouse moreover attempted to apply its techniques in germanium; it soon became apparent that silicon was more suitable material for IC fabrication.

in a single IC component. The Air Force contracted to pay three-quarters of the cost of this three-year programme which formed about one third of the firm's R & D effort in integrated circuitry.[23] Fairchild, on the other hand, deliberately rejected Air Force offers of R & D funding although the company sold prototype IC's to the government at innovation premium prices.[24] *Aggregate expenditure by government agencies on integrated circuit R & D funding during the period 1959-64 inclusive has been estimated at thirty-two million dollars, the Air Force accounting for some seventy per cent of the total.*[25] *As integrated circuitry gained ground over competing micro-electronic approaches, the overwhelming weight of Air Force funding gave way to a more even distribution between the three military services and NASA within the context of a greatly increased appropriation.* During 1964, the Air Force allocation accounted for rather less than half aggregate R & D expenditure.

10.2.3 Government Procurement of Integrated Circuits

Despite the efforts of the Air Force to promote the semiconductor approach to microelectronics, it is clear that no concensus existed even in 1962 in either military or industrial circles regarding the most appropriate course to follow. Quite apart from cost considerations, equipment designers hesitated to make use of an unproven component in any quantity. *In retrospect, it appears that two decisions during 1962 were responsible for the requisite breakthrough leading to large-scale acceptance of the IC. NASA announced an intention to utilize ICs for its prototype Apollo spacecraft guidance computer. Then, at the end of 1962, the Air Force publicly stated that an improved version of the Minuteman I ICBM would make maximum practical usage of ICs in its guidance mechanism.* Texas Instruments had been collaborating with the prime contractor, Autonetics Division of North American Aviation (now North American Rockwell), since October, 1961 in an endeavour to promote the application of integrated circuitry. The Minuteman II procurement programme bore many similarities to the earlier Minuteman I exercise. Again, the emphasis

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[23] "Our Growing Components Markets", Electronics, January 5, 1962, p.68.

[24] Organisation for Economic Co-operation and Development, Electronic Components, p.61.

[25] Kleiman, p.201.

rested firmly on the achievement of greatly increased component reliability within a short overall timescale. An exacting schedule called for the design, fabrication and delivery of eighteen new types of ICs within a six month period.[26] Throughout the period of procurement (beginning in 1963), the circuits underwent a complex series of tests designed to identify possible sources of failure followed by appropriate corrective action to eliminate weakness in design or inadequate manufacturing technique.

Texas Instruments (with Westinghouse in a subsidiary role) was awarded the original Minuteman II development and pre-production contract at the end of 1962. Further contracts were awarded during 1963 to Texas Instruments, followed by Westinghouse and RCA, for ICs at prices around one hundred dollars apiece. In October of that year it was estimated that the Minuteman II requirement accounted for some sixty per cent of the value of all IC orders to date.[27] At the same time the NASA Apollo order for a total of 200,000 circuits began to gather momentum. Indeed, during 1963 the Apollo contract led Minuteman II in terms of units supplied though not as regards dollar value. Most of the Apollo circuits were produced by Fairchild. These two major procurement programmes dominated the fledgling IC industry throughout 1963 and the early part of 1964 and together they effectively comprised the overwhelming weight of government demand observed in chapter 5.1. *Encouraged by the success of these programmes, weapons systems contractors began to design equipment incorporating ICs and several additional procurement projects were initiated during 1964. The original participants, Texas Instruments, Fairchild and Westinghouse, obtained further military/space contracts while the surge forward in procurment also enabled emergent contenders like Motorola and Signetics to lift their production volumes.*

10.2.4 The Effect of Government Involvement in Research, Development and Production

While the government has spent considerable sums on R & D via contracts with semiconductor firms, it

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[26] R.C. Pistzek and J.S. Kilby, "Minuteman Integrated Circuits - A Study in Combined Operations". Proceedings of the Institution of Electrical and Electronics Engineers, Vol. 42, No. 12, December 1964.

[27] Electronic News, October 28, 1963, p.42.

is clear from previous discussion that this effort has not been responsible for any of the major inventions. Action by military and space agencies has, however, exerted an indirect effect on the pace and direction of privately-funded R & D projects. Awareness of a consistent requirement for high performance components has undoubtedly served to stimulate the investment of R & D resources in advanced technology areas. *The allocation of substantial government funding to R & D has been, in the first instance, directed at producing a solution to the immediate problem. But it has also performed a valuable catalytic function by further emphasising the urgency of the situation and thereby encouraging the infusion of private resources into the search for a solution. It is clear that this second aspect was well to the fore in at least two cases: the silicon grown junction transistor and the IC. The objective was to create a climate of opinion conducive to innovation. To the "pull effect" of an assured market, the authorities added both the "push effect" of R & D funding and its consequential influence upon privately-funded endeavour.*

Government contracts have, in some circumstances, led to a contraction in the development lead time for a new device. Texas Instruments, for example, received immediate funding for the development of its IC working model which undoubtedly compressed the timescale involved. Moreover, it is evident that government agencies have made a useful contribution to the diffusion of technological expertise in their role as information clearinghouses. Very probably, this function proved especially valuable during the early period when Bell enjoyed a virtual monopoly of semiconductor wisdom. The precise extent to which government-funded R & D contracts have created commercially beneficial technology is rather more difficult to determine. In view of the market shifting pattern observed in chapter 4, one would expect such spillover to be substantial since many devices developed at the behest of the military authorities ultimately enjoy widespread usage in commercial markets. This view receives support from a regression study of 1959 R & D data which suggests that a firm could expect to receive as many patents from government-funded as privately-funded R & D expenditure.[28] But the conclusion is called into question by a 1960 Department of Defense survey in

[28]Tilton, "Firm Size, Government Support and R & D", p.11-13.

which firms acknowledged the existence of very few patents arising out of government-sponsored R & D, only a small proportion being used commercially.[29] Texas Instruments, for example, reported that only five patents out of the 112 awarded to the company between 1949 and 1959 were developed under government contract even though federal sources funded nearly two-fifths of the thirty million dollars spent on R & D. Of these five patents, only two were used commercially, one of the two being a semiconductor patent. The apparent conflict between the two sets of observations is reconcilable by reference to the factors noted in section 10.1, making for a low patent output from government-sponsored R & D and minimal usage thereof.* Spillover does occur but it is not generally recorded in patent statistics either for the reasons given there or because it is not, in any event, amenable to patenting.

Semiconductor firms undoubtedly recognise the existence of this R & D spillover effect and seek to take advantage of it. Companies accordingly select these contracts which appear to hold out to the promise of maximum commercial benefit. Well-established, technologically proficient organisations are naturally better placed to reject contracts with less foreseeable commercial relevance because of a strong demand for their services from the military/space agencies. This tendency may be self-reinforcing in that contracting bodies prefer to award contracts to firms either possessing an existing commercial activity in the field or, at least, professing an interest in ultimate commercial exploitation. *The prospect of commercial gain provides an additional incentive for speedy and successful completion; it also accounts for the willingness of firms to contribute towards the cost. This kind of situation is well illustrated by the major Air Force-Motorola cost-sharing contract negotiated in 1961. Much of the work was orientated towards the development of linear integrated circuitry, an area in which*

[29] U.S. Senate, Subcommittee on Patents, Trademarks and Copyrights, Patent Practices of the Department of Defense, 87th Cong., 1st Sess., 1961, Appendix B.

*(Author's note): Section 10.1 points out that since patents arising out of U.S. government-funded projects are subject to compulsory, royalty-free licensing for military purposes, there is a disincentive to patent these advances. Similarly, there exists an observed tendency among government contractors to minimize the contribution of non-corporate finance and initiative to commercial success.

Motorola maintains a particular interest through its large stake in the manufacture of communications equipment and consumer products. The contract provided a valuable fillip to Motorola's existing IC development programme, accelerating the firm's entry into production.[30] *Texas Instruments is currently engaged on two major Air Force contracts, one concerning LSI concepts and the other relating to microwave integrated circuits. Again, the company is willing to operate on a cost-sharing basis because "these are contracts to explore methods which might, if successfully developed, be used by the industry during the 1970's."*[31]

Production refinement contracts on the IPS model have contributed to the overall development of the industry by forcing firms to focus attention on production technology. Minimum production rate requirements impliedly obliged contractors to direct effort at yield improvement of the direct variety observed in chapter 4 since advances in this direction held out the attraction of extra production at no additional cost. The IPS measures enabled several firms to gain a foothold in the industry but, more particularly, they set the stage for the "shakeout" which occurred in the early part of the 'sixties.

10.2.5 The Effect of Government Procurement Programmes

Previous discussion has indicated, in the light of the usual market shifting pattern, the extreme importance of military/space demand at the inception of a technology. (Chapter 8 demonstrated how early innovative type spin-offs have benefited greatly from the willingness of government agencies to pay commerically prohibitive prices for improvements in performance and reliability.) Firms in receipt of government contracts for the purchase of new-type devices have undoubtedly obtained useful spillover into the non-government environment. The objective of this subsection is to examine this spillover mechanism in some detail.

The influence of the procurement contract at the early stage of exploitation operates through its impact on dynamic economies of scale. Experience in volume production produces yield improvement, mainly of the indirect but immediate variety identified

[30] Electronics, January 5, 1962, p.68.

[31] Arthur D. Little Inc., The Outlook for Integrated Circuits, p.23.

in chapter 4. Operator and managerial learning contribute to dramatic reductions in unit cost for which there is immense scope at the initial low yield rate. *Procurement contracts of the Minuteman II variety are therefore responsible for setting in motion the familiar virtuous circle relationship between volume and price. As price falls, the new device becomes competitive with present devices in industrial equipment and the commercial sector, in turn, begins to exert a powerful influence on volume.* It is after this point that the military begins to derive an advantage from the fruitful series of interactions initiated by them as the emergence of an industrial demand serves to further cheapen the cost of military products. Moreover, a subsidiary feedback mechanism supports the original virtuous circle. Frequently, only a small proportion of the devices made will meet the exacting specifications of the military/space environment. The residual fall-out products are often saleable in the less demanding civil market. Since prices negotiated under the procurement contract invariably include a sufficient margin to cover most development and other fixed costs, the firm is prepared to sell these below military standard items at marginal cost or at a price providing some small contribution to overheads. These "artificially" low prices constitute a great attraction for commercial users and lead to an opening up of the non-government sector earlier than would otherwise be the case.[32]

The actual contribution of dynamic economies of scale in production is, however, considerably dependent on the nature of the typical federal government procurement contract. One significant feature is that purchases have usually been deliverately concentrated in only a few firms. A small number of large orders allows dynamic scale economies to operate with maximum effect; dispersion among several firms would undoubtedly serve to dissipate the impact. A further aspect peculiar to the government procurement contract confers an advantage of a different kind. Contractors receive progress payments which alleviate the strain on corporate cash flow at a time when

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[32]Many of these fall-out planar devices have been sold in Europe in recent years much to the chagrin of home-based manufacturers. For a brief commentary on this point see I.G. Cressell, "The Expanding Field of Micro-Electronics" Survey on Electronics and Automation, Financial Times, December 12, 1966.

outgoings are large. As the management of Fairchild Semiconductor has testified:

> "The missile/space field has created a market in which Fairchild can produce sophisticated scientific products and achieve a fairly rapid payout on its investment in development."[33]

But the essential value of the long-term contract lies in its ability to insulate the recipient firm from the vicissitudes of the market....Long-term contracts confer stability on the vendor. Production planning can proceed secure in the knowledge that it will not be subjected to disruptive variations in the volume and pace of manufacturing activity reflecting fluctuations in orders received. The stability of the long-term procurement contract accordingly provides an environment highly conducive to yield improvement and it is this which often lies at the root of the precipitate reduction in unit cost observable in the early production state of a new device technology.

As in the case of R & D spillover it appears that much of the spillover from government purchasing is indirect and intangible. Devices designed specifically for military/space application cannot normally be sold in the non-government sector without some modification. *Texas Instruments Minuteman II ICs were made available to commercial customers but attracted little attention because of their distinct military orientation. The spillover in this instance was indirect: the firm benefited through the extensive transfer of production experience gained during the course of the programme to the manufacture of commercial devices.* Direct product spillover can, however, occur. Fairchild Micrologic circuits were specifically designed for the general computer field. The NASA Apollo contract and others used these circuits in airborne logic applications conferring specific production experience on Fairchild which enabled it to appeal to industrial buyers with substantial price reductions in May, 1964.

Procurement contracts awarded for missile/space programmes since 1958 have imposed stringent demands on component reliability. The need to meet tight specifications has, in turn, led to more rigorous production and testing procedures which have had a beneficial effect on commercial devices, again of an intangible kind. *The Minuteman Reliability Programmes*

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[33]Welles et al., p.77.

have influenced both the quality and cost of commercial devices. In general, this transfer has not been direct but operated through the application of knowledge and expertise gained from involvement in high reliability exercises to commercial products. Cost reduction occurs in an indirect fashion through the less immediate contribution to dynamic scale economies identified previously: The emphasis on reliability isolates troublesome processes on which R & D resources can then be brought to bear. Enhanced understanding of the faulty process often results in higher yield and reduced cost.

Large-scale purchases of new products have often had a very desirable psychological effect on potential users. This is clear from the history of the IC. *Minuteman II convinced many prospective purchasers by demonstrating the willingness of a branch of the military to place its trust in a radically new and untried component for an important weapons project. Certainly, the net effect of many procurement programmes has been to accelerate market level diffusion. This is again best exemplified by the case of the IC. Average selling price declined from thirty-eight to fifteen dollars between the first and fourth quarters of 1964.*[34] But, at the same time a fourfold increase in units sold more than compensated for the price drop lifting total dollar volume for the year from sixteen to forty-one million. A further fifty per cent reduction in average price for 1965 provided an even greater stimulus to unit sales. Indeed, the speed of events after the introduction of catalogue lines in 1961 exceeded even the most optimistic prophesies. In 1962 Texas Instruments, an IC pioneer with no disposition toward reticence, predicted:

> "A steady growth pattern for integrated circuitry with industry wide sales climbing to a point between \$150 - 200 m. by 1968."[35]
> (The actual figure was \$312 m.)

By the beginning of 1964, however, sales had commenced their upward spiral and Electronics reported that:

> "(Integrated circuits)...are growing up faster than expected. Demand has grown so in the last

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[34] Air Force Systems Command, p.22.

[35] *Business Week*, April 14, 1962, p.182.

few months that even some of the most optimistic manufacturers are startled."[36]

It is clear that the rapidity with which ICs penetrated the American economy must be attributed, in very large measure, to the "pull effect" of government procurement programmes. While there can be no doubt that the IC innovation would have been developed and exploited in any event, the effect of government involvement has been, above all, to compress the time schedule between market introduction and general commercial application.

1973 Report for Department of Commerce

A 1973 report prepared for the Department of Commerce noted the importance of the military in the field of integrated circuit development [12]:

> In the United States, a substantial amount of R & D is sponsored by the Federal government and stimulated by U.S. space and military procurement, especially in the field of IC development.

1975 Study by National Bureau of Economic Research

A study by William F. Finan [6] pointed out the importance of the military market to the growth of semiconductor technology in general and integrated circuits in particular:

> In terms of influence on the growth and direction of semiconductor technology, historically the military market has been the most important; but the computer and consumer markets have superseded the military market.
>
> The military was the largest end-use consumer of semiconductors until the middle sixties. (See Table 2-3). It was willing to pay premium prices to obtain higher performance and reliability. For example, during the first four years integrated circuits were in production (1961 to 1965), the military purchased nearly 90 percent of all circuits produced. Only after the average price per circuit declined 80

[36]"1964: The Year Microcircuits Grew Up," *Electronics*, March 13, 1964, p.10.

percent did other users begin to purchase integrated circuits in substantial quantities.[8] In this same period the number of companies producing integrated circuits in the United States increased from two to over thirty. The military's willingness to utilize the most advanced devices in its equipment encouraged the formation of new companies interested in rapidly developing new avenues of semiconductor technology.[9] This was an important factor in the early development of the industry.

Table 2-3. DISTRIBUTION OF U.S. SEMICONDUCTOR SALES[1] BY END MARKET

End Market	1960[2]	1968[2]	1972[3]
Computer	30%	35%	28%
Consumer	5%	10%	22%
Military	50%	35%	24%
Industrial	15%	20%	26%
Total	100%	100%	100%
Total Value (Millions of $)	560	1,211	1,378

[1]Sales in dollars.

[2]Texas Instruments estimate.

[3]J. P. Ferguson Associates estimate.

1976 Issue of *IEEE Transactions on Electron Devices*

In July 1976 the IEEE Electron Devices Society published a special Bicentennial Issue of the *IEEE Transactions on Electron Devices* which included historical articles by many of the leaders in the development of the semiconductor industry. It is generally agreed that Jack Kilby of Texas Instruments developed the first working integrated circuit. In his article, G.K. Teal stated [9]:

[8]Tilton, op. cit., Table 4-8, U.S. Integrated-Circuit Production and Prices, and the Importance of the Defense Market, 1962-1968, p.91.

[9]For a further discussion of the military's role in the development of the U.S. semiconductor industry see OECD, op. cit., pp.59-65; Tilton, op. cit., pp.89-92.

A specially significant advance was made in 1958, when Jack Kilby of Texas Instruments fabricated the first working integrated circuit....

In his article, Kilby traced the steps leading to the development of the integrated circuit [10]:

> The transistor also suggested concepts based on semiconductor technology. The first to perceive the possibility was G.W.A. Dummer of the Royal Radar Establishment in England.
>
> Addressing the Electronic Components Conference in 1952, he said, "With the advent of the transistor and the work in semiconductors generally, it seems now possible to envisage electronics equipment in a solid block with no connecting wires. The block may consist of layers of insulating, conducting, rectifying, and amplifying materials, the electrical functions being connnected directly by cutting out areas of the various layers."
>
> This remarkable statement was not explicit as to how such devices might be realized. The use of terms such as "insulating" and "amplifying" layers does not suggest the use of circuit techniques. In 1956 Dummer let a small contract to a British manufacturer. They were unsuccessful in realizing a working device, primarily because they were working with grown-junction techniques.
>
> In the early 1950's perhaps as a result of Dummer's comments, the Air Force began to define an approach which would be called "Molecular Electronics." This approach [7] proposed to depart from the electronic circuits of the past, and to develop new structures which would perform the desired functions more directly. A quartz crystal was the preferred example of a molecular device, performing the functions of an inductance and capacitance without a part-for-part equivalence. Resistors were to be avoided because they wasted power. Although the effort was not limited to semiconductors, it was expected that these materials would play a large part.
>
> In 1957 and 1958 the Air Force discussed this concept with Westinghouse, and a contract was awarded in 1959. Representative Air Force equipments were to be examined, and new devices to perform the desired functions were to be systematically invented. The program was funded at a $2 million per year rate, over the strenuous objections of the other services.

> By the beginning of 1958 each of the three services had chosen a position. The Army was heavily committed to the Signal Corps Micro-Module, although DOFL still favored 2-D circuits and continued to work on them. The Navy did not have a program, but clearly favored thin film technology. The Air Force was committed to Modecular Electronics, an approach which was considered hopelessly far out by the other services. Small R & D efforts existed within the major electronic firms, most supporting the Signal Corps or the Navy.

Note the involvement of all three services in this field, and particularly the key role played by the Air Force in "molecular electronics" which was similar to the concept used in the successful development of integrated circuits.

With respect to the actual invention itself, Kilby referred to the military market as his motivator since, as noted above, the Micro-Module mentioned in the following passage was a Signal Corps project:

> ...My duties were not precisely defined, but it was understood that I would work in the general area of microminiaturization. Soon after starting at TI in May 1958, I realized that since the company made transistors, resistors, and capacitors, a repackaging effort might provide an effective alternative to the Micro-Module. I therefore designed an IF amplifier using components in a tubular format and built a prototype. We also performed a detailed cost analysis....
>
> The cost analysis gave me my first insight into the cost structure of semiconductor house. The numbers were high--very high--....In my discouraged mood, I began to feel that the only think a semiconductor house could make in a cost-effective way was a semiconductor. Further thought led me to the conclusion that semiconductors were all that were really required--that resistors and capacitors, in particular, could be made from the same material as the active devices.
>
> I also realized that, since all of the components could be made of a single material, they could also be made *in situ*, interconnected to form a complete circuit.

Kilby then went on to describe his development of the first working integrated circuit in the last half of 1958 at Texas Instruments.

> The first working units of this type were completed early in 1959 and were later used for the first public announcement of the "Solid Circuit" (integrated circuit) concept at the IRE show in March 1959.

This initial development work was supported by Texas Instruments' corporate funds. However, Kilby then related the important support subsequently provided by the Air Force (italics added):

> During the fall, we began to inform the military services of the concept. Reactions were mixed. The Navy had little interest, and no programs were established. The Signal Corps expressed some interest and began to define a contract which would show that the technique would be fully compatible with the Micro-Module. Unfortunately, the demonstration they had chosen required silicon p-n-p transistors. These proved quite difficult to fabricate, and by the time the techniques were mastered, the Micro-Module program was in serious trouble.
>
> The "Solid Circuit" concept caused a major debate within the Air Force. A substantial budget had been established for work in Molecular Electronics. If the "Solid Circuit" was indeed a Molecular Electronics concept, support was assured. But most of the strong Molecular Electronic supporters felt that the TI approach did not qualify. It was a circuit, and they were not going to have circuits any more. Worst of all, it even had resistors, and resistors wasted power.
>
> Fortunately, a small group within the Air Force, led by R.D. Alberts of WADC, was able to prevail. They felt that the concept provided an orderly transition to the new era, and that by providing a systematic design approach, it eliminated the need to invent the thousands of new devices which would be required for future equipments.
>
> *Albert's group then provided the first of a series of contracts which proved invaluable in sustaining the project during the critical years. These included both research and development efforts to broaden the concept, and manufacturing methods funds which helped*

> *support the first manufacturing line. Demonstration vehicles which clearly showed the advantages of these new techniques were also included.*

In describing the early production of integrated circuits, Kilby mentioned two Air Force procurements (italics added):

> Because of the commonality with existing processes, integrated circuits moved rapidly into a production status. The first TI device for customer evaluation was announced in March 1960. In March of 1961, Fairchild announced the Micrologic[1] family, a compatible set of digital circuits incorporating junction-isolated diffused resistors and evaporated interconnectors. In October of that year, *TI delivered to the Air Force a small working computer* complete with a few hundred bits of semiconductor memory, and announced the Series 51. The Series 51[2] also used junction-isolated components and used variations in the evaporated interconnection pattern to produce six different circuit types. Since a portion of the Series 51 effort was supported by NASA, these circuits were designed for low-power applications.
>
> *In 1962 TI was awarded a large contract to design and build a family of 22 special circuits for the Minuteman missile.* Fairchild received substantial contracts from NASA and a number of commercial equipment makers. Although only a few thousand units were delivered in 1962, the year represented the beginning of mass production.

1976 Issue of *IEEE Spectrum*

This magazine included an article on "The Genesis of the Integrated Circuit" [21]. In his summary at the end of the article, the author reported that:

> Although the work at TI and Fairchild was not the molecular electronics the Air Force was advocating, and although Fairchild intentionally avoided Government funding for its efforts, Kilby and Noyce agree on the

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[1]This family was designed by Bob Norman and built by a group headed by Jay Last.

[2]The Series 51 was designed by Bob Cook. Process Technology was developed by a group under Jay Lathrop.

importance of the military in establishing the motivation to miniaturize as well as in ultimately becoming the first customer for the new circuits.

1977 Issue of *Science*

A recent article by Drs. Linvill and Hogan[1] included some discussion of the support by the government (mainly DoD) of the semiconductor industry [5]. Most of their comments, excerpted below, involved the semiconductor industry in general; those sections dealing specifically with integrated circuits have been italicized. However, it should be remembered that integrated circuits were developed by the semiconductor industry and depend on the same technology. The Linvill/Hogan article mentions that in 1966 only 14 percent of the sales of semiconductor manufacturers consisted of integrated circuits; by 1976 the corresponding figure was 58 percent.

> The importance of the transistor to defense electronics was immediately obvious. Army, Navy, and Air Force agencies immediately began the support of transistor electronics for the defense need. The pursuit of excellence was intense; competition developed among the various defense agencies to support the best ideas and the best teams in the various industrial laboratories and in the universities. Moreover, the commonality of interest among the contractors to the federal government promoted the high diffusion rate of new information in semiconductor electronics.
>
> ...Governmental support of semiconductor R & D was large. From 1958 through 1974, various branches of the U.S. government pumped $930 million into research and development in the semiconductor industry. A very legitimate debate exists today as to whether government support of R & D in this industry has been as pivotal as the demand by military and space efforts for the devices manufactured by the industry. Very little objective data exist that can be used to support either side of this debate.

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[1]Dr. Linvill is chairman of the Department of Electrical Engineering, Stanford University. Dr. Hogan is vice chairman of the Board of Fairchild Camera and Instrument Corporation. Both are alumni of Bell Laboratories.

...The U.S. Department of Commerce has published figures indicating that private industry supported $1.2 billion of R & D during the same period of time. So, all together, American industry was able to put more than $2 billion into R & D during this 16-year period.

...In addition to R & D expenditures by the U.S. government, another important component of governmental support was contracts for production preparedness. Very early in the history of the transistor, the U.S. Army, Air Force, and Navy supplied capital dollars to the American semiconductor industry to build production equipment in order to have a capability to produce these new devices. The first such dollars were supplied in 1952 so that our industry could build production lines to manufacture alloy transistors.

While many companies were willing to support R & D efforts in this exciting new technology in 1952, few would have had the courage to build multimillion dollar production lines at such an early date. This expenditure would have required the approval of the board of directors of the companies involved, and even if they had the foresight at that early time to begin production, their approval would have introduced a delay of at least several months. With the funds available from the U.S. government, an enterprising manager could build a production line without the approval and perhaps even without the knowledge of his board of directors.

As early as 1952 many American companies were motivated to build production lines for alloy transistors. Those who did found the business profitable. They got an early jump on their competitors who were still justifying this daring move. This technology diffused as rapidly through the United States as did R & D knowledge. Even though this initial investment by the U.S. government to build alloy transistor lines amounted to only $11 million, it provided a critical time advantage.

In 1957, the U.S. government provided another $15 million to industry to buy capital equipment to build production lines for diffused-base transistors. Again, while this amount was small compared to the money that private industry had to put up, it nevertheless gave an initial stimulus. *As early as 1959, the services supplied another $10 million to American industry to buy or build the equipment necessary to build a production capability for integrated circuits.*

Now, it is true that the $36 million supplied by the U.S. government in these contracts is a fraction of what our industry had to supply itself in order to build the enormous production capability that we now have. Nonetheless, the U.S. Signal Corps and Air Force, in particular, deserve credit for the foresight that they had so early in the game which led them to supply these needed capital dollars.

Many Americans argue that a large majority of the companies that got this early production support do not now exist as semiconductor suppliers and, hence, that the money was wasted. This is nonsense. Two of the largest recipients of the U.S. government support in the early days were Texas Instruments and Motorola. They did survive, and this early help was critical in helping them to an early start in the business. As for the companies that received support and failed, other successful companies hired their people and American industry was automatically farther along on the production learning curve because of the investment.

The largest markets in semiconductor electronics from the invention of the transistor through the middle 1960's were the computer industry and the military-aerospace industry. Two customers, because of their use volume, were absolutely pivotal in the early establishment of American semiconductor firms.

The first was IBM. In 1960, IBM was probably the largest single customer of every American semiconductor company. *The second major customer was the Minuteman missile system. This missile system poured hundred of millions of dollars into the semiconductor industry at a very important time in its history. This money went into diffused transistors and integrated circuits; in particular, it provided funds necessary for the refinements to achieve a high level of reliability for semiconductor devices.* All subsequent semiconductor systems benefited from the technological advances with the new levels of electronic reliability.

More detail is given on the Minuteman reliability achievement elsewhere in the paper. In 1958, a failure rate of 0.0007 percent per 1,000 hours was required with a then-current failure rate for transistors of about 1 percent per 1,000 hours. Improvements were achieved in about three years that reduced failure rates to about 0.0003 percent per 1,000 hours.

Linvill and Hogan conclude that indeed there has been a spinoff in semiconductor electronics from early use in defense and space to use in other areas:

> This electronics revolution has been fueled by a science base, promoted by government agencies vitally interested in the implements it promised, and carried out by new ventures with bold managers who perceived the opportunities and delivered outstanding performance. Electronics has grown in its utilization to address the urgent problems of defense and space, and its development from application to these problems has stimulated use in other areas. The $0.5-billion U.S. semiconductor business in 1960 was about half government and half private. By 1975, the $1.75-billion semiconductor industry had only a 22 percent government portion. We foresee that further development will proceed in the industrial and consumer sectors from the start already evident.

C. THE VALUE OF INTEGRATED CIRCUITS TO DoD

The left panel of Table C1 indicates that DoD purchases of integrated circuits increased rapidly and then stabilized around $140 million per year from 1967 through 1972. Although not a small amount of money, the true value of integrated circuits to DoD is much greater than indicated by these figures. The reason is that integrated circuits are used in weapon systems costing billions of dollars and their availability has greatly improved the cost-effectiveness of these very expensive systems.

This value can be appreciated from a review of the impact of integrated circuits on the Minuteman missile. Minuteman I was designed before integrated circuits were available. In 1962, the Air Force was seeking to increase the range of Minuteman with no decrease in payload or reliability. To design a new, higher performance propulsion system would involve a costly and lengthy program of propulsion system development and testing. An alternative way to increase the missile's range was to reduce the size and weight of the existing electronic guidance package [14]. The latter approach was selected and the guidance package was redesigned using integrated circuits.

The use of integrated circuits resulted in a 50 percent reduction in the weight of the guidance package, which permitted

Table C1. VALUE OF SHIPMENTS OF INTEGRATED CIRCUITS

Year	All Integrated Circuits[a]			Monolithic Integrated Circuits Only[a,b]		
	Total (Millions of Dollars)	Defense (Millions of Dollars)	Defense as Percent of Total	Total (Millions of Dollars)	Defense (Millions of Dollars)	Defense as Percent of Total
1962	--	--	--	4	4	100
1963	--	--	--	16	15	94
1964	--	--	--	41	35	85
1965	317	70	22	85	61	72
1966	492	98	20	158	84	53
1967	505	126	25	252	108	43
1968	568	143	25	335	126	38
1969	751	127	17	452	109	24
1970	888	147	17	567	120	21
1971	815	138	17	543	102	19
1972	1,052	146	14	555	82	15

Source: [a] *1965-1972: Shipments of Selected Electronic Components for Calendar Years 1960-1969, 1970, 1971, and 1972,* U.S. Department of Commerce, 1970, 1971, 1972, and 1974, respectively.

[b] 1962-1964: Estimated by Tilton, *op.cit.*, Table 4-8.

the desired increase in range [7, 14]. The reliability improvement resulted from the greater reliability of the integrated circuits relative to the previously used discrete components [7, 14]. The improved guidance package also resulted in reduced logistics costs [7] and provided about twice the functional capability of the discrete model used in Minuteman I [16].

The successful use of integrated circuits demonstrated in the Minuteman II program led to their rapid application in many other military systems. Their advantages of high reliability and small size and weight were particularly valuable in missile, spacecraft, and aircraft applications. However, they quickly found their way into virtually all types of electronic equipments procured by DoD. For example, in the few years following the Minuteman II program, they were used in the following equipments, among many others:

Samos satellite
R45 multimode airborne radar
R47 system-backup radar
Semiactive guidance system (SAGS)
D26 computer family
"Trisafe" triple redundant automatic stability augmentation system
N16 inertial navigation system
Phoenix air-to-air missile
Mark 48 torpedo
PCM telemetry encoder
Cable sonar submarine-detection system
AN/UCC teletypewriter radio transmission system
Navy E-2A aircraft
USMC tactical data system
AN/GXC facsimile equipment
TF-600 secure communications system
Laser rangefinder
Lance missile telemetry equipment
PCM data buffer subscriber set.

D. THE ROLE OF NASA IN DEVELOPING INTEGRATED CIRCUITS

Other Government agencies also contributed to the development of integrated circuits. This section discusses the role of NASA, the predominant contributor of these other Government agencies. Tables D1, D2 and D3 present data on expenditures by DoD and NASA on various classifications of electronics. Table D1 is the only series dealing specifically with integrated circuits; it covers R&D funding only. Table D2 presents total federal expenditures for electronics, while Table D3 covers only R&D expenditures. In each of these tables NASA expenditures as a precent of DoD expenditures are presented in the final column. These percentages are presented for easy comparison in Table D4. In addition, the middle column of Table D4 presents percentages for R&D support to the semiconductor industry from the special DoD survey data included on page 11 of this paper. That survey reported only DoD and "other government" expenditures, the latter being 10 and 13 percent of DoD expenditures for the two years covered by the survey. Since other-than-NASA government agencies were included in these figures, the NASA portion would necessarily be less than the percentages shown.

Although the last three columns of Table D4 include more than just integrated circuits, they help in giving some feel for the relative importance of DoD and NASA in the various aspects of the electronics industry, and probably in the integrated circuit portion of the industry as well.

All the figures indicate that NASA's expenditures prior to 1963 were less than 10 percent of those of DoD. NASA was established in late 1958 (the time of the invention of the integrated circuit) and contributed little to the development of the integrated circuit from its invention to the time its production became significant around 1963. Starting in 1963 and extending through about 1968, however, NASA played a much more significant role through its large scale application of integrated circuits in the Apollo program. During this period, the figures of Table D4 indicate that NASA expenditures in the field of integrated

Table D1. INTEGRATED CIRCUIT RESEARCH AND DEVELOPMENT FUNDING

Year	Millions of Dollars					NASA as Percent of DoD
	Air Force	Army	Navy	DoD Total	NASA	
1959	3.12	0	0	3.12	0	0
1960	2.98	0.70	0.11	3.79	0	0
1961	4.67	0.95	0.41	6.03	0.14	2
1962	3.78	0.87	0.46	5.11	0.11	2
1963	4.20	0.65	0.38	5.23	0.24	5
1964	2.20	0.81	1.17	4.18	1.36	33

Source: [15, p. 20]. Based on *Commerce Daily*, NASA files, USAEC, press literature, interviews]

circuits probably ran in the range of 20-40 percent of DoD's expenditures. Following this peak period of Apollo program expenditures, NASA's expenditures again declined to a much lower level relative to DoD's.

The following interesting discussion of NASA's role in the introduction of integrated circuits was included in Kleiman's dissertation [15]:

> The role of NASA in the introduction of the IC device is very negligible, if any. Its influence in the development of the technology, however, has been considerable both directly and indirectly. There are three major categories in which the space agency has made a positive contribution to the IC cause: climate, R&D sponsor, customer.
>
> Climate--The role of space in our national thinking went from insignificant to imperative in late 1957. The United States, always prideful of its technological prowess and innovative expertise, had been bettered by its cold war adversary. The Soviet Union, ravaged by a World War, had only joined the "modern world" in the second decade of the twentieth century and had achieved one of the most magnificent scientific feats known to man. It cast a long shadow on our own national and international prestige. Its initial conquest could not

Table D2. FEDERAL FUNDS FOR ELECTRONICS

Year	Millions of Dollars							NASA as Percent of DoD
	DoD				NASA			
	Procurement	RDT&E	O&M	Total	Procurement	RDT&E	Total	
1960	--	700	--	5,038	--	--	200	4
1961	4,300	2,000	1,000	7,300	100	100	200	3
1962	4,900	3,000	1,300	9,200	200	300	500	5
1963	4,521	1,935	1,568	8,123*	--	--	1,195	15
1964	4,518	2,000	1,482	8,000	--	--	1,675	21
1965	4,133	1,830	1,357	7,320	--	--	1,715	23
1966	4,462	1,975	1,464	7,901	--	--	1,745	22
1967	4,916	2,245	1,815	8,976	--	--	1,793	20
1968	4,577	2,291	1,996	8,864	--	--	1,622	18
1969	4,714	2,300	2,030	9,044	--	--	1,486	16
1970	5,754	2,329	2,134	10,217	--	--	1,160	11
1971	5,007	2,592	2,153	9,752	--	--	985	10
1972	5,126	2,692	2,240	10,058	--	--	948	9
1973	5,181	2,848	2,361	10,390	--	--	825	8
1974	5,630	3,420	2,565	11,615	--	--	750	6
1975	6,166	3,943	2,751	12,860	--	--	784	6
1976	6,783	4,416	2,850	14,049	--	--	795	6

*Includes "other."

Source: *Electronics*, January issues, 1962-1977.

Table D3. FEDERAL FUNDS FOR RESEARCH AND DEVELOPMENT, ELECTRICAL EQUIPMENT AND COMMUNICATION (SIC CODES 36, 48)

Year	Millions of Dollars			NASA as Percent of DoD
	DoD	NASA	Total Federal	
1958	--	--	1,337	--
1959	--	--	1,642	--
1960	--	--	1,675	--
1961	--	--	1,596	--
1962	--	--	1,691	--
1963	1,200	300	1,849	25
1964	1,120	264	1,873	24
1965	1,130	468	1,983	41
1966	1,292	497	2,201	38
1967	1,437	404	2,296	28
1968	1,536	431	2,345	28
1969	1,614	343	2,412	21
1970	1,520	281	2,261	18
1971	1,531	310	2,302	20
1972	1,740	244	2,492	14
1973	1,907	215	2,655	11

Source: *Research and Development in Industry*, 1969 and 1973 issues, National Science Foundation, NSF 71-18 and 75-315, respectively.

be erased, but the United States could become superior in space technology and accomplish even greater achievements before the Russians; maybe we could even perform some space feat that the Russians couldn't duplicate. There is no doubt that these objectives became a very real part of our national purpose, initiated in the late Eisenhower years and raised to an almost chauvinistic plateau during the Kennedy Administration. NASA officials, capitalizing on this nationalistic fervor, could translate the intangible feeling into very real objectives for the electronics industry and those serving it. Electronic equipment, it was emphasized, was

Table D4. COMPARISON OF NASA WITH DoD FUNDS FOR ELECTRONICS

	NASA Funds as Percent of DoD Funds			
Year	Integrated Circuit R&D[a]	R&D Support to Semiconductor Industry[b]	Total Funds for Electronics[c]	Electrical and Equipment Communication R&D[d]
1958	--	<10	--	--
1959	0	<13	--	--
1960	0	--	--	--
1961	2	--	3	--
1962	2	--	5	--
1963	5	--	15	25
1964	33	--	21	24
1965	--	--	23	41
1966	--	--	22	38
1967	--	--	20	28
1968	--	--	18	28
1969	--	--	16	21
1970	--	--	11	18
1971	--	--	10	20
1972	--	--	9	14
1973	--	--	8	11
1974	--	--	6	--
1975	--	--	6	--
1976	--	--	6	--

Sources: a. Table D1.
b. From page 11.
c. Table D2.
d. Table D3.

indispensable to the space mission, and the electronic equipment wasn't good enough for the task. There was no reason why it should have been, since the needs of a space age were unprecedented. Both in kind and degree, the requirements for space had no predecessor. A new look was called for, and the semiconductor components industry, so vital to the electronics function, had to lead the way since the equipment generally is no better than its component parts. On another level, the military was repeating the same theme. Reliability must be improved not only because of the importance of the military mission which might depend upon the required electronic equipment, but also for the long-run reduction of supporting costs. The NASA motivation was not translated into a dollars and cents issue. The economic cost of unreliability is great, as has been obvious in several of the more recent space failures. Even now, however, with the increased awareness to cost considerations, failure is stressed relative to its effects on a scheduled timetable and possible consequences if that schedule falls very far behind. Undoubtedly, the NASA influence had and still has a reinforcing effect for the military exhortations that preceded it. It has also raised these urgings to a level and degree of critical importance which the military could not duplicate. Military problems are more insulated and restricted to the agencies involved and their contractors. NASA's problems are more all-pervasive, simply because of the importance accorded it and the publicity which has always accompanied its mission. The general public has been involved.

R&D sponsor--This area, of the three cited here, has probably been the one in which the space agency has had the least impact upon the advancement of the IC technology. This is attributable to two reasons: the level of the funding and the nature of the programs being sponsored.

NASA's role as an R&D sponsor compared to that of the Air Force has been insignificant....In the late fifties, there was no NASA support at all; NASA was founded in late 1958. In the early sixties, it began some modest funding, and in recent years it has become a much more active R&D participant. Generally, however, other than the normal advantages which a company may gain from Government support of its R&D programs--increased income, greater experience in the device technology, encouragement to venture into new areas not normally supported by non-Government applications--the NASA influence in the R&D area has been slight.

Secondly, NASA's needs are very special and particular to its own tasks. Besides reliability improvement, it puts a high premium on reduced size and weight and lower power consumption. These are characteristics desired by the various military agencies to a lesser degree; they have very little priority in industrial-consumer applications. Even within the military establishments, there are very few programs that can approach the NASA needs in their high priority on these aspects of electronic performance. Therefore, the type of IC work supported by the R&D programs of NASA may be relegated to a very limited spectrum of applications and, as a result, limited interest beyond these areas.

Customer--The Apollo guidance computer will use integrated circuits on its trip to the moon. Other parts of the Apollo vehicle and other programs of the space agency have used IC components, but this project has, for several reasons, carried the greatest impact.

In fall of 1962, when the decision was made to use IC devices in the prototype computers for the Apollo mission, these new components had not been designed into any major program for any application. (The Minuteman contract was announced in December of that year publicly stating that the advanced version of the missile would use integrated circuits.) Although the Apollo decision did not necessarily mean the devices would be incorporated into the actual computers, it did definitely imply that NASA and its contractors thought enough of these components' potential to consider their use. This was a major accomplishment. The new technology had gained an adherent who had enough faith in it to consider it for the most important mission of the whole space program and to use the IC devices in a critical area where electronic failure was probably equivalent to mission failure or at least a diminution of mission effectiveness. The influence of this decision, impossible to measure, must have been a powerful stimulus on systems designers who were still "on the fence" whether to include the IC device in their own designs. Needless to say, it probably gave the semiconductor industry a tremendous lift, since this was the first indication of a justification of the great effort and expenditure which had gone into the technology up to that point. If members of the industry, either those already committed to integrated circuits or those considering such a move, were hesitant about the future of the technology, NASA's decision should have done a great deal to allay such fears. To complete the story, NASA more recently made the definite decision that IC components will be used in the Apollo guidance computer.

In a much more immediate and tangible sense, the NASA action meant that the industry was to have its first volume purchase. In late 1964, one reporter noted that 200,000 integrated circuits had been purchased to that date for the Apollo manned spacecraft project (which includes more than the computer).[24] Considering the time when these devices were being sold, $20 per item would probably be a low figure. If this was the true average price, the revenue would have been $4 million. When one considers the importance of this amount of dollar income and unit volume, it is easy to realize the salutary effects which this purchase conveyed for the other IC products being offered by the firms involved. In the spring of 1964, Fairchild Semiconductor, which supplied the major share of the IC devices for the Apollo computer program, was the first to offer an off-the-shelf IC product line that was directly aimed at stimulating the non-military, non-space market. It is highly unlikely that the firm could have made this move if it did not have the NASA support for its higher-priced integrated circuits. At the least, the firm's capability to move in this direction was facilitated by the significant NASA support it had. Soon after, two of the other major IC vendors followed Fairchild's example; now all the major participants supply low-cost devices compatible with the needs of industry and, hopefully someday, the consumer market.

The actions and policies of NASA accelerated the acceptance of integrated circuits, although its greatest activity as a customer is yet to come. Space efforts of the future will use an increasing number of these devices, and the impact of NASA as an R&D sponsor and as a customer should be considerably more important than it has been in the past.

Note that Kleiman wrote the above in 1965 or 1966 and that NASA, in the post-Apollo period to date, has failed to grow as predicted in Kleiman's last paragraph.

Some additional comparative detail on the Minuteman II and Apollo programs was presented by Golding [3]:

Texas Instruments (with Westinghouse in a subsidiary role) was awarded the original Minuteman II development and pre-production contract at the end of 1962. Further contracts were awarded during 1963 to Texas Instruments, followed by Westinghouse and RCA, for IC's at prices around one hundred dollars apiece. In October of that year it was estimated that the Minuteman II requirement

[24] Barry Miller, "Microcircuitry Production Growth Outpaces Applications," *Aviation Week*, November 16, 1964, p.79.

> accounted for some sixty per cent of the value of all IC orders to date.[27] At the same time, the NASA Apollo order for a total of 200,000 circuits began to gather momentum. Indeed, during 1963 the Apollo contract led Minuteman II in terms in units supplied though not as regards dollar value. Most of the Apollo circuits were produced by Fairchild. These two major procurement programmes dominated the fledgling IC industry throughout 1963 and the early part of 1964 and together they effectively comprised the overwhelming weight of government demand.... Encouraged by the success of these programmes, weapons systems contractors began to design equipment incorporating IC's and several additional procurement projects were initiated during 1964. The original participants, Texas Instruments, Fairchild and Westinghouse, obtained further military/space contracts while the surge forward in procurement also enabled emergent contenders like Motorola and Signetics to lift their production volumes,

Although it appears that the production of integrated circuits for the Minuteman II and Apollo programs were roughly comparable in the 1963-1964 period, DoD used more integrated circuits for other programs than did NASA; hence, it is unlikely that NASA ever equalled DoD in its expenditures for integrated circuits. More likely, at its peak of relative importance, NASA probably expended about 20-40 percent as much for integrated circuits as did DoD, per the figures of Table D4.

E. THE MARKETS FOR INTEGRATED CIRCUITS AND FOR PRODUCTS USING INTEGRATED CIRCUITS

1. The Market for Integrated Circuits

An annual report on the value of U.S. shipments of integrated circuits is published by the Department of Commerce [18]. The middle column of Table E1 shows the latest published sales of integrated circuits. The final column, obtained in discussion with Department of Commerce personnel, shows expected revisions of the 1974 and 1975 figures, and their best guess (as of February 1977) of the 1976 figure. These figures include all

[27] *Electronics News*, October 28, 1963, p.42.

Table E1. VALUE OF SHIPMENTS OF INTEGRATED MICROCIRCUITS

Year	As Published[a] (Millions of Dollars)	Expected Revision[b] (Millions of Dollars)
1966	135	--
1967	227	--
1968	331	--
1969	459	--
1970	465	--
1971	584	--
1972	1,138	--
1973	1,724	--
1974	2,122	2,056
1975	1,516	1,890
1976	--	2,270

Source: [a] *Current Industrial Reports: Selected Electronic and Associated Products, Including Telephone and Telegraph Apparatus, 1975*, U.S. Department of Commerce, September 1976.

[b] From discussion of N. J. Asher, IDA, with Department of Commerce personnel.

integrated circuits sold, transferred to other plants of the same company, or shipped on consignment; also included are all products whether for domestic consumption or for export. Imports are excluded. These figures are higher than some published figures which are for sales only and do not include production for internal use. IBM and Western Electric are large producers of integrated circuits but do not sell them to other equipment manufacturers.

The data of Table E1 include all types of integrated circuits. Table E2 shows the breakdown by type of integrated

Table E2. VALUE OF SHIPMENTS OF INTEGRATED MICROCIRCUITS BY TYPE (MILLIONS OF DOLLARS)

	1975	1974
Hybrid integrated circuits, thick or thin film composed of material deposited by silk screen process on a passive substrate combined with discrete active or passive components	116	274
Hybrid integrated circuits, thick or thin film composed of material deposited by vacuum deposition, sputtering or similar process on a passive substrate combined with discrete active or passive components	77	51
Hybrid integrated circuits, multichip; circuits not incorporating film techniques. These are usually combinations of chips, active and/or passive. Discrete package devices may be used for some, but not all of the circuits	36	41
Thin or thick film integrated circuits composed entirely of passive elements on a passive substrate	16	11
Monolithic digital integrated circuits:		
DTL (diode transistor logic)	29	49
TTL (transistor transistor logic)	227	326
CML/ECL (current mode logic/emitter coupled logic)	54	97
MOS (metal oxide silicon)	445	487
Other digital including diode logic, complimentary transistor logic resistor transistor logic/direct couple transistor logic, etc.	304	522
Monolithic analog integrated circuits	212	264
Integrated Microcircuits (Semiconductor Networks) TOTAL	1,516	2,122

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circuit for 1975 and 1975. Monolithic integrated circuits have progressively accounted for more of the total integrated circuit market over time. In 1965 they accounted for only about 27 percent of the total market value. As can be seen from Table E2, monolithic integrated circuits accounted for 82 percent of the total value in 1974 and 84 percent in 1975.

The Department of Commerce published another series of reports which included a breakdown of defense shipments relative to total shipments (see Table C1, page 73). Unfortunately, this series was discontinued after 1972 because of the refusal of some of the companies to continue divulging the necessary data. The series as published by the Department of Commerce started only in 1965; Tilton [2] estimated the monolithic sales for the three prior years.

Table C1 shows that the percent of shipments to the military were quite high in the early years and have declined as integrated circuits penetrated first the industrial and then the consumer markets. Note that defense accounted for relatively more of the monolithic sales than of total sales in the early years, but by 1972 the percentage going to defense was about the same for both monolithic and total. Table C1 shows the importance of the military in providing an early market for integrated circuits, particularly in the case of the monolithic type which offers the greatest potential for improvement over the previous generation of discrete components.

Note that Tables E1 and C1 both show approximately $1.1 billion in total integrated circuit sales in 1972, but that figures for the earlier years are considerably higher in Table C1 than in Table E1. Department of Commerce personnel indicated that they feel the Table C1 figures for the pre-1972 years are better than those of Table E1. The figures of Table C1 were derived from the *Quarterly Survey of Production Capabilities for Electronic Parts* conducted by the Bureau of Domestic

Commerce; those of Table E1 were derived from the Bureau of the Census annual Form MA-36N, *Selected Electronic and Associated Products, Including Telephone and Telegraph Apparatus*.

The total market for integrated circuits rose from a few million dollars in 1962 to about $1.1 billion in 1972 and about $2.3 billion in 1976. According to a recent article in *The Wall Street Journal*, sales in 1977 are expected to increase still further [19]. Hence, the value of integrated circuits now (1977) being produced in the U.S. is running at a rate of $2.5 billion or so. However, integrated circuits are not an end product--they are only used in making other equipment. Hence, there is a multiplier effect on their value. Some products now being produced would simply not exist in the marketplace if integrated circuits were not available. The cost-effectiveness of other previously existing products has been greatly enhanced through the incorporation of integrated circuits. In the next section we will discuss the degree of impact on various types of products that are using integrated circuits.

2. The Market for Products Using Integrated Circuits

As noted in the section above, the value of integrated circuits being sold by U.S. firms in 1977 is about $2.5 billion. However, the value of the products in which they are used is much greater than that. In Table E3 products using integrated circuits are grouped according to the importance of integrated circuits to the success of the product. The 1977 dollar sales estimates were derived from *Electronics* magazine's annual forecast [22]. A three-level scale was used in this appraisal as follows:

- Essential--Products which could not be produced (or if physically producible, the end product would not be affordable to the prospective buyer) without ICs;

Table E3. 1977 SALES OF PRODUCTS USING INTEGRATED CIRCUITS

	Estimated Sales ($ Million)
Essential	
Hand-held Calculators	420
TV Games	230
Electronic Watches and Clocks	590
Major Impact	
Data Processing Systems, Peripherals, and Office Equipment	17,420[a]
Modern PABX's	40[b]
Satellites, All Types	--[c]
Automotive Electronics	440
Data Communications	1,010
Hearing Aids, Pacemakers	290
Industrial Machine Control	1,410
Analytical Instruments	205
Minor Impact	
Entertainment (TV, Radio, HiFi)	5,760
CB Radios	1,000

Source of Sales Dollars: *Electronics*, January 6, 1977.

Notes: [a]Excludes $3,200 million of office equipment such as copiers and dictation equipment.

[b]Ten percent of total non-Bell market.

[c]Not known. $65 million for satellite earth stations.

- Major Impact--Products which could be produced without ICs but whose cost, size, power consumption, or other performance parameters are improved to a major degree through the use of integrated circuits;
- Minor Impact--Products which have benefited to a limited degree from the use of ICs through reduced cost, improved performance, improved reliability, or other parameters.

It should be noted that we consider hybrid as well as monolithic ICs in this assessment of products using integrated circuits.

The product categories were assigned on a judgmental basis. It is believed that "Data Processing Systems, Peripherals and Office Equipment" as a whole belongs in the Major Impact category because the machines sold today are more than an order of magnitude more capable than the transistor-only machines and have nearly displaced transistor-only machines from the market. It could be argued that the value of the market for a displaced product should be subtracted from the estimate. This was not done here in accordance with custom (e.g., the displaced market for buggies is not typically subtracted from the automobile market).

Each major category was scanned to determine that all subelements were appropriate to include. For example, when "Data Processing Systems, Peripherals, and Office Equipment" was appraised, it was found to contain $3,200 million of office equipment which were not impacted to a major degree by integrated circuits. The total was reduced accordingly. This procedure was followed for each product class.

As can be seen from Table E3, the total market value of products using integrated circuits is much greater than the $2.5 billion direct sales value of integrated circuits themselves.

The markets for two of the products for which integrated circuits are essential are discussed in the following sections.

3. Desktop and Handhand Calculators[1]

The availability of integrated circuits has revolutionized the desktop calculator market and has created a completely new market for handheld calculators.

Prior to 1965, this market was comprised of electromechanical calculators, with about five U.S. firms supplying a large portion of the U.S. market. This was essentially a mature market. The dollar value of product shipments grew at an average annual rate of slightly more than 5 percent between 1958 and 1965, and the average unit value of calculators remained relatively stable over this time period, falling from $487 in 1958 to $450 in 1965. The 1965 figures of Table E4 are comprised virtually entirely of electromechanical calculators. Note that the U.S. was a net importer of these machines. "U.S. Apparent Consumption" equals domestic shipments minus exports plus imports. Because of the high unit price of these machines, typical users were accountants, statisticians, and engineers who, because the machines provided indispensable calculating capabilities in their work, could justify the machine's expense.

From 1965 to 1970, a transition occurred from the electromechanical type to electronic calculators. However, many of these machines utilized discrete electronic components such as transistors, and the use of integrated circuits was not widespread. During the period from 1966 to 1970, U.S. *production* remained fairly constant, while U.S. *consumption* roughly doubled due to imports of Japanese electronic calculators. However, many of these Japanese imports utilized U.S.-produced electronic components.

The big expansion in the electronic calculator market started in 1971, when several U.S. firms announced the

[1]This material is from *The Impact of Electronics on the U.S. Calculator Industry, 1965 to 1974*, U.S. Department of Commerce, November 1975.

Table E4. U.S. CALCULATOR SHIPMENTS AND CONSUMPTION

Year	U.S. Domestic Shipments			U.S. Apparent Consumption		
	Value (Million $)	Units (Thousand)	Unit Value ($)	Value (Million $)	Units (Thousand)	Unit Value ($)
1965	69	153	450	80	288	278
1966	90	182	495	112	415	270
1967	81	172	472	119	531	224
1968	78	165	471	141	677	205
1969	97	175	553	192	1,005	191
1970	83	129	646	224	1,386	161
1971	134	335	398	276	1,890	146
1972	233	958	243	338	2,661	127
1973	440	4,814	91	639	9,568	67
1974	551	7,571	73	785	15,402	51
1975	436	9,010	48	667	23,998	28
1976	360[a]	9,010[a]	40[a]	580[a]	29,500[a]	19[a]
1977					35,200	

[a]These figures estimated by Department of Commerce personnel. All others from *The Impact of Electronics on the U.S. Calculator Industry, 1965 to 1974*, U.S. Department of Commerce, November 1975.

incorporation of all the logic and memory circuitry necessary for a four-function calculator on a single integrated circuit chip. Not only did this make is possible to reduce an electronic calculator to true handheld size, but it further simplified the manufacture of the calculator. The first U.S.-produced handheld calculator appeared on the market in September of 1971, retailing for $240. By December, the retail price had fallen to $180 and by mid-1972 the price was down to $150. Producers and distributors now saw the potential of a new untapped mass market--the household or consumer market.

Table E4 shows the dramatic growth of this market. From 1971 to 1976, U.S. domestic shipments increased from 335,000 to 9 million units. Table E4 shows a unit value of $398 in 1971, dropping to $40 in 1976. However, some units produced in 1971 were still of the electromechanical type, which were relatively expensive; they were virtually out of production by the end of 1972. As noted above, the domestically produced handheld types dropped from about $240 in 1971 to about $40 in 1976.[1] Total value of U.S. production increased from $134 million in 1971 to $551 million in 1974, but then dropped to about $360 million in 1976 due to the continued sharp decrease in unit prices. Table E4 indicates that U.S. consumption was much greater than U.S. production over this period, increasing from about 1.9 million units in 1971 to almost 30 million in 1976. The Department of Commerce projects total consumption of about 35 million units in 1977; however, their dollar value will probably be about the same as in 1976 due to continuing decreases in unit prices. In other words, roughly one calculator will be sold for every six U.S. citizens in 1977. Combined with the stock of calculators already in use, the ubiquity of the calculator in our everyday

[1] The unit values of Table E4 are averages. According to Reference [20], prices of the cheaper units dropped from $100 in 1972 to $20 in 1974, with the first $10 units appearing in 1975, and price tags as low as $8 in 1976.

lives is truly amazing. Without the availability of integrated circuits, such widespread use of calculators would not have occurred.

4. Electronic Watches[1]

The digital electronic watch is paralleling the calculator in the rate at which sales are growing and prices are declining--but where the calculator is a brand new product, the electronic watch is a technology-based improvement on an existing product.

Virtually unknown before 1972, electronic digital watches sold in the $200 range in 1973, when approximately 250,000 were marketed. Sales doubled in 1974, according to industry estimates, then rose to at least 2,500,000 in 1975, with sales of 5 million or more widely forecast for 1976. True to electronics' ability to deliver better products at lower prices, electronic watches came within virtually everyone's budget in 1976, with the introduction of units retailing for less than $20.

It's estimated that the factory value of electronic watches sold in the United States last year totaled more than $200 million, and this figure should nearly double in 1976.

Electronic watches, like calculators, employ large-scale integrated circuits and electronic readouts. Most of these sold in the United States incorporate light-emitting diode (LED) glowing numerals, but an increasing number use liquid-crystal displays (LCD), which provide extended battery life. Most digital watches do more than merely tell the time--many also give day and date, and some double as stopwatches. They all have one characteristic in common: extreme accuracy generally unobtainable by all but the highest-priced mechanical watches.

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[1]This material is from *1976 Electronic Market Data Book*, Electronic Industries Association, 1976.

The growing digital watch industry, dominated by American semiconductor manufacturers, is reversing a long-term trend. Production of many American-developed consumer products has moved overseas. But the timepiece industry, long dominated by imports, is now coming home--through electronics.

A more recent article [23] announced that Texas Instruments has dropped the price of its most popular digital watch to $10, and the price of its lowest-price model to $7.50. The article notes "the dizzying pace of price-cutting--from $2,000 to $10 in just over five years--...." A Texas Instruments spokesman estimated that 15 million digital watches were sold in the U.S. in 1976--triple the forecast of 5 million units given in the *1976 Electronic Market Data Book*.

5. <u>Microprocessors</u>

The application of integrated circuits as microprocessors seems likely to exceed all other applications. Originally developed to solve a major problem of the integrated circuit industry (the cost of circuit design), the microprocessor--the computer-on-a-chip--has radically changed all applications of programmed logic. Microprocessors convert hardware problems into programming tasks; they are physically large-scale integrated circuits embodying generalized computer logic.

From $300 million in 1977 microprocessor sales are expected to grow to $1 billion by 1980 [24]. The range of products that can productively employ microprocessors is enormous. Firms are adapting them to automobiles, stoves, microwave ovens, refrigerators, radios, telephones, television, dryers, clocks, and typewriters. Microprocessors also are being used in industrial applications. They have reduced the cost of process control a hundredfold over that of twenty years ago, they save energy, and they permit decentralized automation. Consequently, virtually all major industrial equipment will incorporate microprocessors.

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